U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB80-108962

Setting Priorities for Control of Fugitive Particulate Emissions from Open Sources

Harvard School of Public Health, Boston, MA

Prepared for

Industrial Environmental Research Lab, Research Triangle Park, NC

Aug 79

United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

EPA-600/7-79-186
August 1979

EPA

PB80-108962

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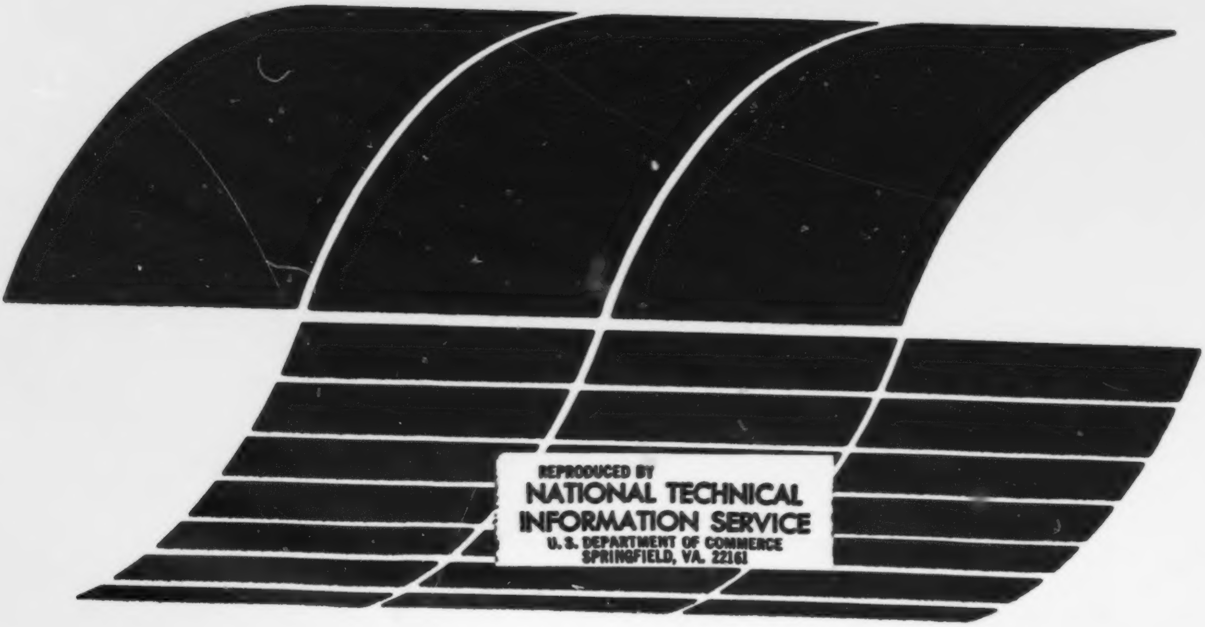
Interagency Energy/Environment R&D Program Report



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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-79-186	2.	3. RECIPIENT'S ACCESSION NO. PB 80 108962
4. TITLE AND SUBTITLE Setting Priorities for Control of Fugitive Particulate Emissions from Open Sources		5. REPORT DATE August 1979
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) D.W. Cooper, J.S. Sullivan, Margaret Quinn, R.C. Antonelli, and Maria Schneider		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Harvard University School of Public Health Boston, Massachusetts 02115		10. PROGRAM ELEMENT NO. EHE624A
		11. CONTRACT/GRANT NO. Grant R805294
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 9/77 - 5/79
		14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is Dennis C. Drehmel, Mail Drop 61, 919/541-2925.

16. ABSTRACT

The report describes setting priorities for controlling fugitive particulate emissions. Emission rate estimates of suspended particulates from open sources in the U.S. were obtained from emission factors and source extents in the literature. Major open sources, with their estimated total emission rates (in millions of tons per year), are: unpaved roads, 300; construction activities, 30; wind erosion of cropland, 40; paved roads, 8; and wildfires, agricultural tilling, and mineral extraction, each 3. (For comparison, point sources of particulates in the U.S. are estimated to emit about 20 million tons per year.) Open source emissions are estimated for each state. Most open source rates are correlated with each other and state population is strongly correlated with the total rate and with most of the source types. The use of cost effectiveness is compared. Paving unpaved roads should reduce emissions at an average of less than $0.01/lb for such states as RI and DE (for rural roads) and AK, AZ, CA, DE, MI, NV, PA, CO, FL, IL, IN, KY, MD, MA, NJ, NM, OH, RI, TN, TX, UT, VA, WA, and WV (for remaining unpaved municipal roads). The control of unpaved road emissions (generally by paving), especially in cities, and the control of emissions from construction activities are concluded to deserve high priority in the effort to reduce total suspended particulate levels.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Roads	Pollution Control	13B	
Emission	Construction	Stationary Sources	14B	13M
Processing	Farm Processing	Fugitive Emissions	13H	02C
Leakage	Fires	Particulate		13L
Ranking	Minerals	Mineral Extraction	12B	08G
Dust Control				

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 136
	20. SECURITY CLASS (This page) Unclassified	22. PRICE A07 - A01

EPA Form 2220-1 (9-73)

EPA-600/7-79-186
August 1979

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Grant R805294
Program Element No. EHE624A

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U.S. ENVIRONMENTAL PROTECTION AGENCY
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ABSTRACT

Emission rate estimates of suspended particulates from open sources in the United States were obtained from emission factors and source extents in the literature. The major open sources, with their estimated total emission rates (in millions of tons per year), are: unpaved roads, 3×10^2; construction activities, 3×10^1; wind erosion of cropland, 4×10^1; paved roads, 8; wild fires, agricultural tilling, and mineral extraction, each 3. (For comparison, point sources of particulates in the U.S. are estimated to emit about 20 million tons per year.) Open source emission rates are estimated for each state. Correlations among these rates (and with state area and population) show that most open source rates are correlated with each other and that state population is strongly correlated with the total rate and with most of the source types. The use of cost-effectiveness is defended. It is shown that the paving of unpaved roads should reduce emissions at an average of less than $0.01 per pound for such states as RI and DE (for rural roads) and AK, AZ, CA, DE, MI, NV, PA, CO, FL, IL, IN, KY, MD, MA, NJ, NM, OH, RI, TN, TX, UT, VA, WA, WV (for remaining unpaved municipal roads). These cost figures are estimates, and particular situations may differ greatly from the conditions assumed. Linear regression of state-by-state annual geometric mean TSP values versus open and point source emissions rates showed that variations in open sources emissions contributed less to variations in TSP readings (per ton of material emitted) than did variations in point source emissions. Particle toxicity and transport characteristics deserve consideration, too, but the literature indicates that the predominant contribution to total suspended particulates (TSP) measurements is soil-like material. The control of unpaved road emissions (generally by paving), especially in cities, and the control of emissions from construction activities are concluded to deserve high priority in the effort to reduce TSP levels.

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SECTION 1

INTRODUCTION AND SUMMARY

Of the 3215 counties in the U.S., 424 are not meeting the current EPA standards for particulates, and this is true of the majority of the country's urbanized areas with populations greater than 200,000.[1] Our research goal was to investigate setting priorities for the reduction of particulate emissions from open sources, following a systems analysis approach: goal definition, problem identification, formulation of assessment criteria, comparison of alternatives. As the work progressed, it became evident to us that the first three steps of such an analysis were not sufficiently advanced that we would be able to compare all the major alternatives for control of open sources. Instead, having settled on cost-effectiveness as our criterion for comparison of alternatives, we performed a cost-effectiveness analysis on the source we estimated to have the greatest emission rate of suspended particulates: emissions from unpaved roads.

BACKGROUND

One reason open sources have received increased attention is that the steady improvement in total suspended particulate (TSP) concentrations in the early 1970's was at least temporarily reversed in 1976. Figure 1.1 (from reference 2) shows a box plot of the national geometric mean daily TSP readings from 1970 to 1976. (The upper and lower edges of the boxes are the 75th and 25th percentiles; the triangle is the average; the point in the box is the median; the dark squares connected by lines to the box are the 90th and 10 percentiles.) In 1976, TSP values increased rather than decreased. Analysis of the events associated with 1976 indicated:[2] "Large areas of the country experienced drought during 1976, and these extremely dry soil conditions increased the likelihood of wind-blown dust contributing to ambient TSP levels....dry soil conditions existed in those general areas that had TSP increases." Further, the results of an assessment of the particulate material captured on filters in 14 major cities in the U.S. indicated that mineral matter (mostly soil-like material) predominated over other types of particulate material, including combustion products.[3]

Figure 1.2 (from reference 6) shows the Air Quality Control Regions (AQCR's) having violations in the first half of 1976 of the EPA TSP primary standards. (In some instances, only a few of the sampling locations, such as in a major city, within an AQCR may exceed the standard yet the entire AQCR has been shaded.) The violations in the West are surprising if only point sources are considered. The pattern is more easily understood when the effects of emissions from open sources - roads, agricultural areas - are considered.

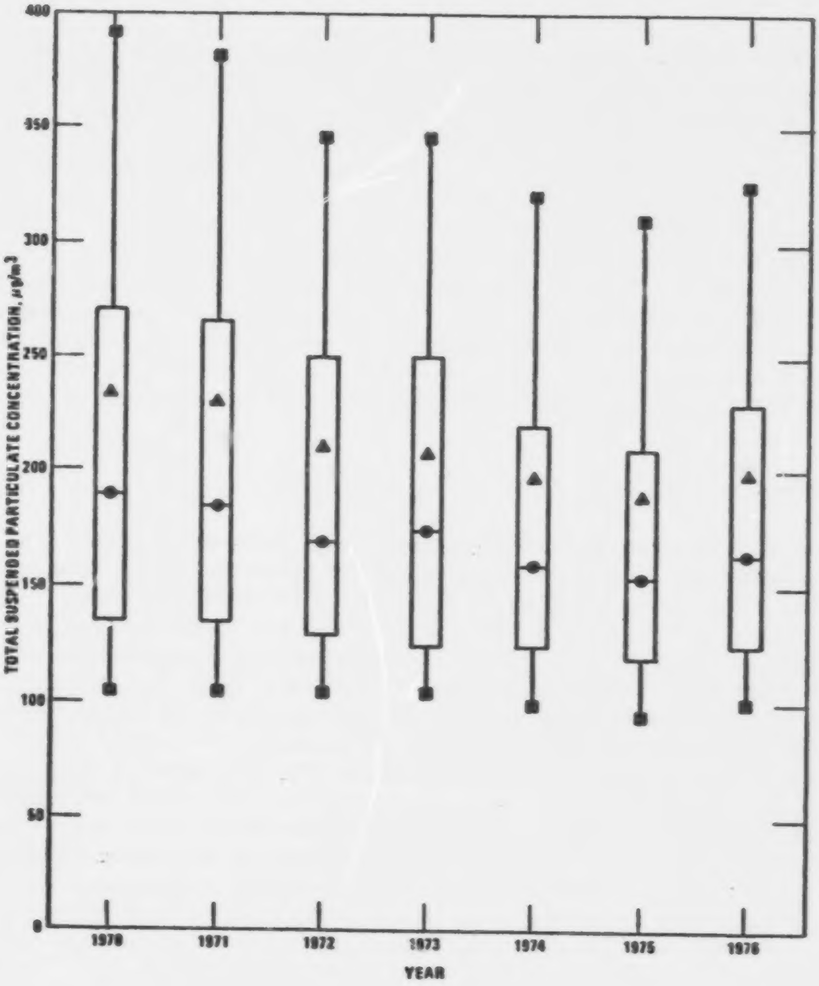

Figure 1.1. Trends of peak daily total suspended particulate concentrations from 1970 to 1976 at 2,350 sampling sites.[2]

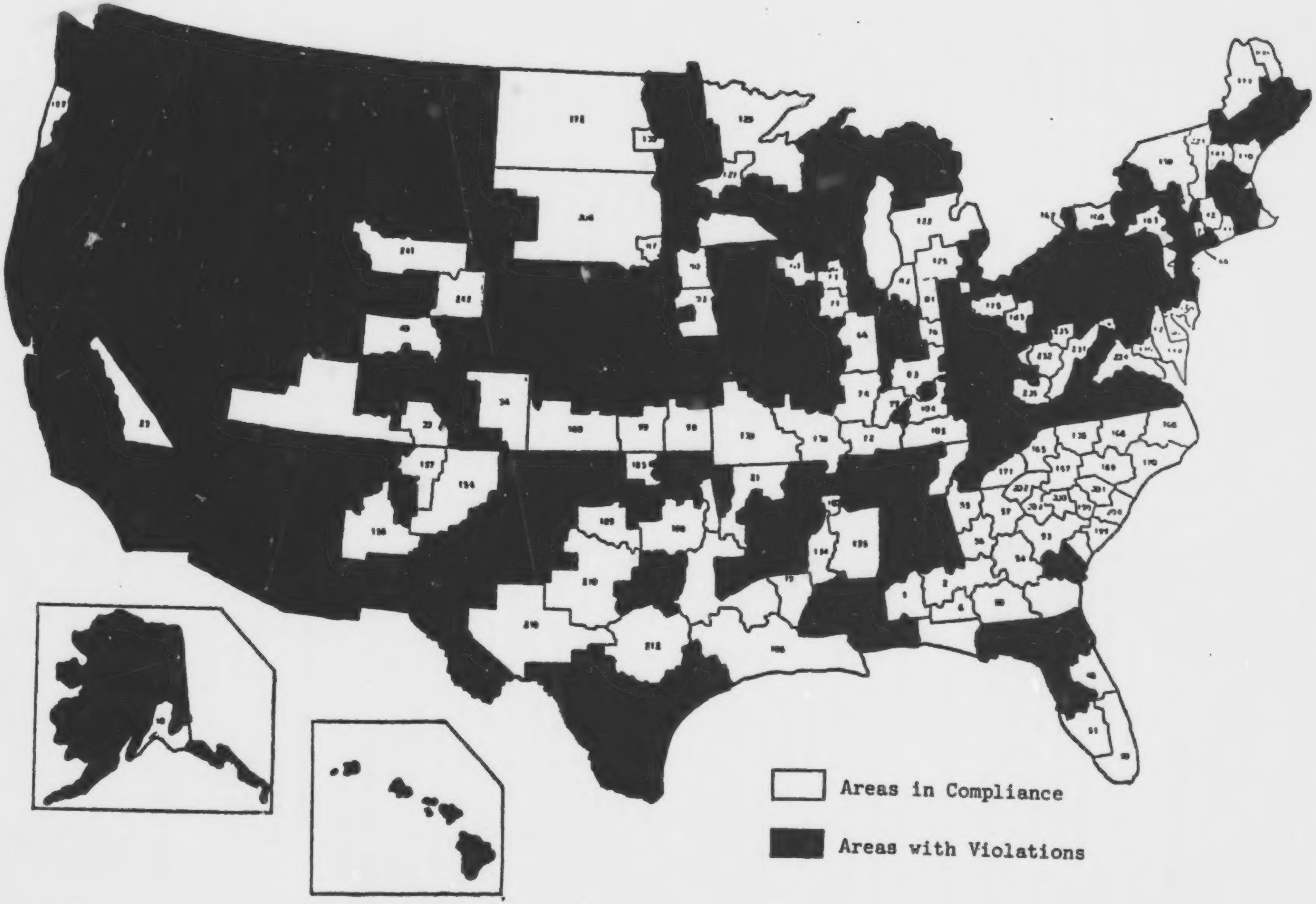
Areas in Compliance
Areas with Violations

Figure 1.2. AQCR status of compliance with ambient air quality standards for suspended particulates.6

GOAL DEFINITION

A proper goal would be the equitable minimization of the costs of pollution control and the costs of pollution damage. The difficulties in finding such an equitable minimization are discussed in Chapter 2. Essentially, one requires some agreed-upon measure of equity and accurate information on the emissions, emissions control, and the connection between the reduction of emissions and the reduction of pollution damage in terms of costs. Such an equitable minimization is probably impossible to determine.

PROBLEM IDENTIFICATION

One way of stating the problem is that emissions from open sources contribute to failures to meet the E.P.A. standards for particulate concentrations in many localities nationwide. Determining which sources contribute most would require a knowledge of the connection between emission rates and concentration measurements. At least an initial understanding of the problem could be obtained by determining which open sources contributed most (as mass rate emitted). The results of our using emission factors and source extents from the literature to calculate emission rates are given in Table 1.1. More details are presented in Chapter 3 and in Appendices A, C, D, E, and G.

Unpaved roads are estimated to have the largest emission rates of the major open sources. Total emissions of particulates from point sources have been less than 20 million tons per year for several years. In contrast, our unpaved road emission estimate is fifteen times this, and construction emissions and wind erosion of cropland are also estimated by us to exceed the point source emissions. Admittedly, the estimates of open source emissions are crude, but it is unlikely they are wrong by an order of magnitude; such sources are certainly greater in magnitude than point sources. Whether or not their impact on particulate concentrations in populated areas is as important as those from point sources depends upon particle transport and relative toxicities, matters that deserve further study. Results of air sampling in cities suggests that soil-like particles are the major contributors to suspended particulate concentrations, as discussed below.

Our emission estimates were aggregated to the state-wide level, as it is generally on this level that governmental control decisions will be made. Chapter 3 presents frequencies and correlations by state for the various types of open sources of particulates and also identifies those states with the greatest and least mass rates of emission in each category.

ASSESSMENT CRITERIA

In Chapter 4, it is argued that cost-effectiveness—achieving the maximum reduction in emissions (or in concentrations or in doses) for a given expenditure—is the appropriate criterion to apply to evaluate con-

TABLE 1.1. ESTIMATED TOTALS OF ANTHROPOGENIC OPEN SOURCE PARTICULATE EMISSION RATES FOR THE UNITED STATES

EMISSIONS TYPE	ESTIMATED EMISSION RATE (10^6 tons per year)	RANK
agricultural tilling	3.2	6
wind erosion of cropland	44.	2
construction	27.	3
wild fires	3.4	5
prescribed fires	0.43	10
minerals: extraction		
-coal	0.4	9
-other	2.8	7
minerals: tailings	0.8	8
paved roads	7.9	4
unpaved roads	320.	1
TOTAL	409.	
TOTAL, NON-ROAD	81.	

trol alternatives, in conjunction with equity considerations.

Initially, we intended to use a cost-benefit approach to optimize control of open sources. The costs of control were to be determined as well as the benefits. The benefits would be estimated by the procedure outlined in Figure 1.3. Having obtained emission rates (from emission factors and source extents), we would use a (simple) dispersion model to predict mean concentrations, then factor in population distributions and dose-response information to predict health effects. Health costs and values assigned to person-years of healthy or sick life would then be used to estimate the benefits to be obtained from changes in emissions. Recently, the relationships between total suspended particulate concentrations and health effects have been summarized by Lave and Seskin.[7] Medical costs and lost earnings are not adequate for estimating the value of lost years of life, as we discussed in a progress report for this project, and as Howard[8] has argued in a recent paper on the proper methodology for estimating the value an individual places on a small incremental probability of premature death. Almost as good a measure would be the cost of alternative ways of saving lives. Lacking proper information for evaluating the benefits of pollution control, we have chosen to investigate the least-cost reduction of emissions.

COMPARISON OF ALTERNATIVES: UNPAVED ROADS

In Chapter 5, cost-effectiveness is applied to the control of unpaved road emissions. The least-cost technique is judged to be paving of roads, and states are ranked from those for which paving would produce the greatest reduction in emissions per dollar to those for which the reductions would be least. (Rural and municipal roads are distinguished.) The statewide average costs per pound of particulates prevented from being emitted are estimated to range from $\leq$ \$0.005/lb. (DE, CA, MD, NJ) to about \$0.06/lb. (SC).

CONCLUSIONS

The conclusions in Chapter 6 relate primarily to the areas in which more investigation is warranted. The conclusions others will draw from the results in Chapters 3 and 5 and Appendices C, D, and G will depend on their perspectives and responsibilities. It seems incontestible, however, that open sources are major contributors of particulate material which is measured as total suspended particulates, both in urban and in rural areas, and that control of such particulates in many areas can be much less costly than control of some industrial emissions in those areas.

DISCUSSION

This analysis indicates that open sources may well contribute more primary particulate material than do point sources and may be less expensive to control, at least in one important case, unpaved roads. The emission inventory approach used in this report estimates mass rates of emissions as

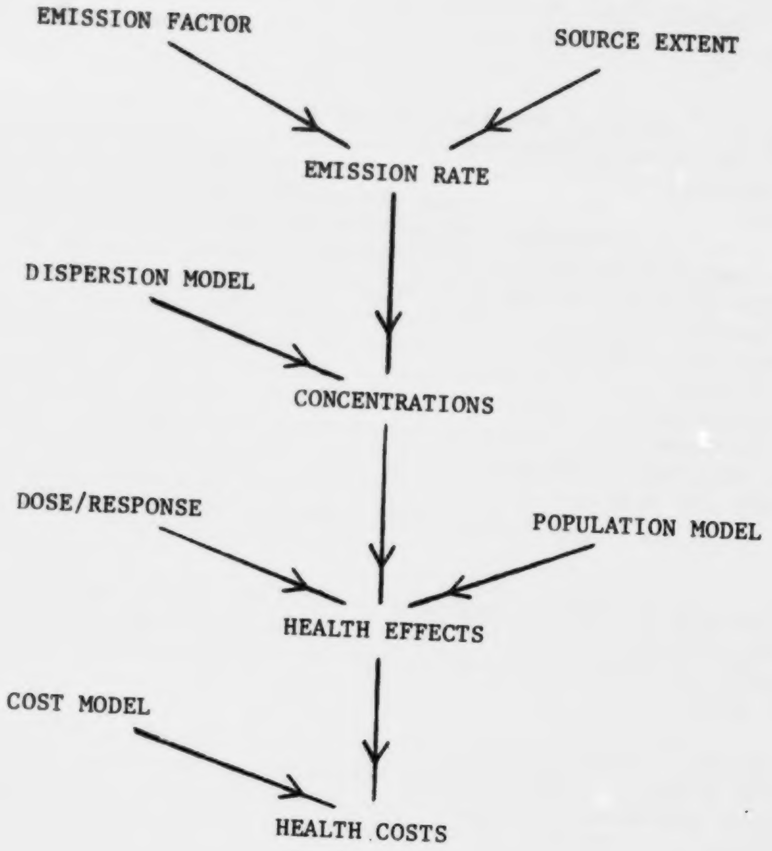
EMISSION FACTOR
SOURCE EXTENT
EMISSION RATE
DISPERSION MODEL
CONCENTRATIONS
DOSE/RESPONSE
POPULATION MODEL
HEALTH EFFECTS
COST MODEL
HEALTH COSTS

Figure 1.3. Flow chart: estimation of source impact.

a means of assessing the relative impact of different source types on air quality. This necessarily neglects transport. A complementary approach is that of using air sampling and analysis to determine the sources of particulate materials that are airborne in populated areas. The results of several such sampling and analysis studies corroborate our conclusion that sources of soil-like particles, such as unpaved roads, construction, wind erosion, and paved roads are primary contributors to measured TSP levels.

Lynn et al.[3] selected fourteen cities in the contiguous United States and analyzed 300 filters from high-volume samplers in these cities. They used these analyses to determine the major contributors to measured TSP concentrations. They concluded that the traditionally-studied point sources are sometimes dominant, especially in heavily industrialized areas, and they estimated such sources contributed to about 15 μg/m^3 in residential areas and over 60 μg/m^3 in heavily industrialized areas. Non-traditional sources, primarily those open sources which are the subjects of this report, were estimated to contribute about 25 to 35 μg/m^3 to citywide TSP levels. Lynn et al.[3] found that the particulates, by mass, had an average of about 65 percent mineral matter versus about 25 percent combustion products. Denver and Oklahoma City, "both areas of dry climate with acknowledged fugitive dust problems," had averages of over 80 percent minerals. They concluded, "Even the cleanest cities (with respect to traditional sources) will be 30 to 40 μg/m^3 above the local nonurban levels due to nontraditional sources."

With respect to reentrained dust from paved roads, Lynn et al.[3] concluded, "The average impact on monitors reviewed in this study was about 10 to 15 μg/m^3 in residential areas and 15 to 20 μg/m^3 in commercial and industrial areas...."

Lynn et al.[3] found it difficult to specify the contribution of dust from unpaved roads: "...the current emission factors given in AP-42 provide emission estimates that can be up to 30 times the emissions from traditional sources." Table 1.2[3] shows emission inventory (not air sample analysis) estimates of emissions from unpaved roads and from traditional sources for fourteen major counties in the United States. Unpaved road emission estimates ranged from much larger than to much smaller than those of traditional sources, from city to city. It was noted that unpaved road emissions and traditional emissions have different particle sizes and release heights and therefore may not make the same contribution to airborne concentrations per mass emitted.

Lynn et al. also concluded that construction activities can be important:[3] "Monitors within half a mile of construction may have annual geometric means 10 to 15 μg/m^3 higher than normal. On an annual basis, the effect on the citywide TSP level is expected to be only 1 to 3 μg/m^3 .... As with reentrained dust from unpaved roads, the currently available emission factors for construction activity provide estimates of fugitive dust emissions well above what would appear logical in terms of the TSP

TABLE 1.2. COMPARISON OF FUGITIVE DUST EMISSIONS FROM UNPAVED ROADS WITH TRADITIONAL SOURCE EMISSIONS IN MAJOR COUNTIES OF 14 AQCR'S[3]

AQCR	Major county	Emissions from unpaved roads, tons per year	Emissions from traditional sources, tons per year	Ratio
Baltimore	Baltimore City[a]	510	7,000	0.07
Birmingham	Jefferson	193,000	110,000	1.75
Chattanooga	Hamilton	N.A.	10,300	–
Cincinnati	Hamilton	76,990	56,100	1.37
Cleveland	Cuyahoga[a]	18,800	210,000	0.09
Denver	Denver[a]	1,270	9,700	0.13
Miami	Dade	70,940	8,000	8.88
Oklahoma City	Oklahoma	85,920	2,600	33.55
Philadelphia	Philadelphia[a]	2,660	31,600	0.08
Providence	Providence	139,830	7,800	17.88
San Francisco	San Francisco[a]	660	4,800	0.14
Seattle	King	197,770	7,300	27.17
St. Louis	St. Louis City[a]	1,220[b]	15,600	0.08
Washington, D.C.	District of Columbia[a]	100	5,600	0.02

[a] These counties are almost totally urbanized so the travel on unpaved roads is expected to be minimal.

[b] This represents the emissions from St. Louis County, a much larger, less urbanized area; actual reported emissions for St. Louis City were 159,900 tons/year suggesting a coding error confusion with the county.

levels actually observed."

Figure 1.4 and Table 1.3 summarize the estimates by Lynn et al.[3] of the impact of non-traditional sources on air quality. (They cited a figure of 0.66 million tons of vehicle tire tread wear per year, which is a much smaller mass rate than those of the major open sources we have identified; these particles were generally the largest found on the filters and there is some question as to their true contribution to the mass concentration.) Table 1.3[3] gives particle size information on minerals, combustion products, biological material, and rubber from the 300-filter analysis.

Confirmatory evidence that soil-like particulates are major contributors to the TSP levels in cities as well as rural areas came from work recently published by Klappenbach and Goranson[5]. Noting that 15 October 1976 had many reported TSP values (24-hour samples) exceeding secondary (150 $\mu g/m^3$) standards, they analyzed by microscope material caught that day on the filters of hi-vol samplers for six sites: Fish Creek, WI; Madison, WI; Milwaukee, WI; Chicago, IL; Moline, IL; Peoria, IL. The particles were examined and identified as to chemical type (such as quartz, fly ash, spores, salt) and the percentages (by count) were listed by the detailed descriptions under four rather general categories: minerals, combustion products, biological materials, miscellaneous. The minimum detectable particle size was estimated to be 1-2 μm. The percentages attributed to minerals (the kind of material emitted by open sources) ranged from 72 percent (Fish Creek, WI) to 91 percent (Moline, IL; Milwaukee, WI); the Chicago value was 84 percent. The authors conjectured that agricultural activity was responsible, but their evidence was inconclusive. It was, however, a period in the area which was more dry and more windy than average, which would increase emissions from agriculture, roads, and construction.

Almost all open sources are at ground level. If, as we believe, they contribute substantially to the ambient concentrations of particulates in the cities as well as in rural areas, then one would expect that urban concentrations would decrease from the ground level up. This is exactly what Pace et al.[4] found in a study of the concentrations measured by 31 high-volume air samplers in 7 urban commercial areas. Subtracting estimated nonurban and secondary particulate contributions, the residual concentrations were found to decrease with high height, following a relationship well-fitted ($r^2=0.47$) by the equation:

$$c(z) = b + a/z \qquad (10 \text{ ft} \leq z \leq 100 \text{ ft})$$

where

$c(z)$ = adjusted concentration at z, $\mu g/m^3$

z = height of monitor above ground level, ft

$b = 23.5\ \mu g/m^3$

$a = 381.6$ ft-$\mu g/m^3$.

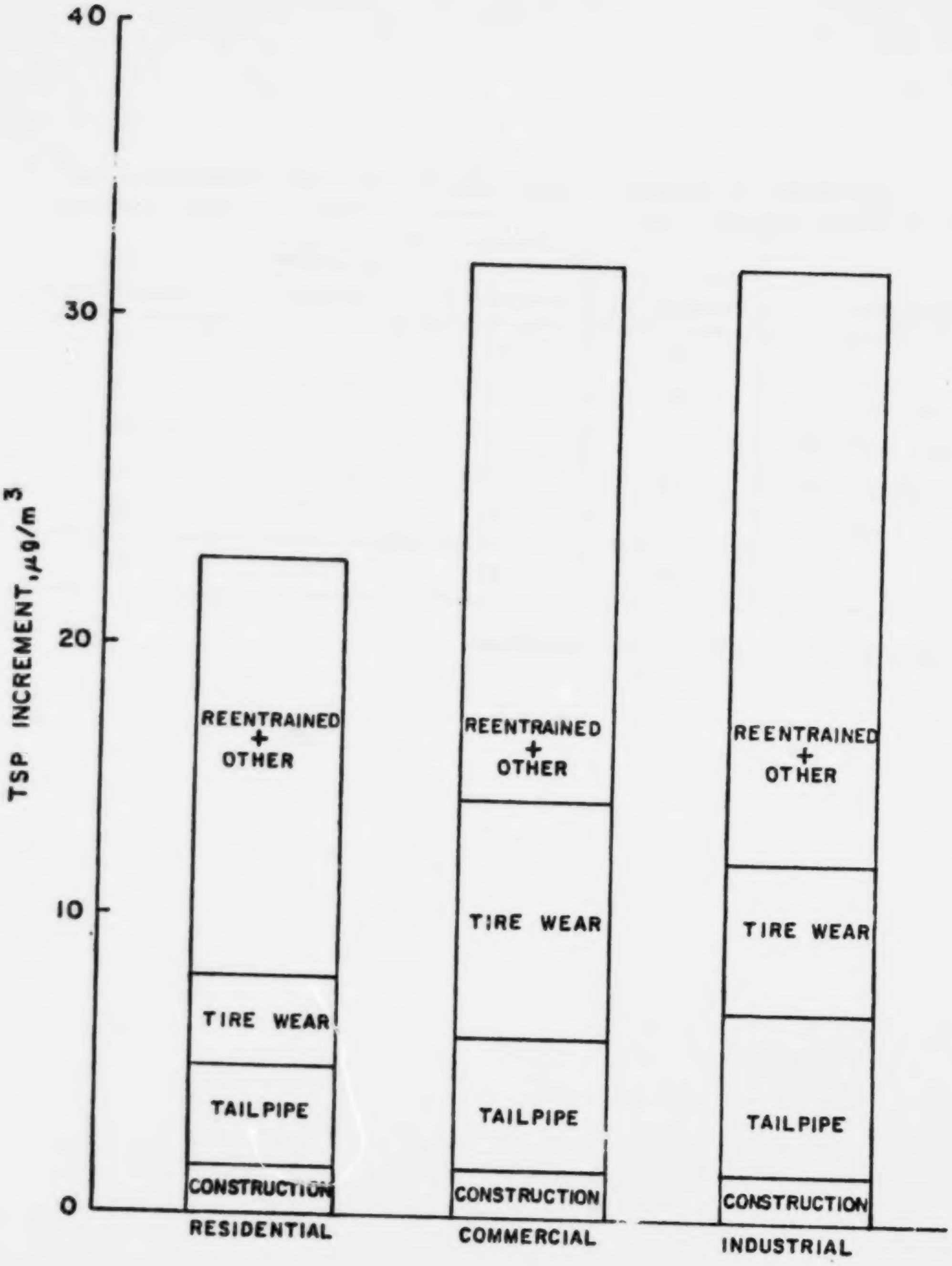

Figure 1.4. Nontraditional source increments at different site types.[3]

TABLE 1.3. ESTIMATES OF AVERAGE FILTER LOADINGS BY SITE CLASSIFICATION[a][3]

Components	Average loading, $\mu g/m^3$			
	Commercial	Residential	Industrial	Undeveloped
Mineral	64	51	87	66
Combustion products	27	19	42	6
Biological material	2	3	3	<1
Misc. (mostly rubber)	9	5	9	<1
Assumed < 1 μm	19	14	25	13
Total	120	92	166	86

[a] Based on a total of 300 filters analyzed.

TABLE 1.4. COMPOSITE SUMMARY OF PARTICLE SIZE BY COMPONENTS[a] [3]

Component	Average size, μm	Average size range, μm	No. of filters included in averaging
Minerals	(8)	<1-62	153
Quartz	11	2-65	154
Calcite	9	1-45	148
Hematite	3	<1-39	89
Combustion Products	(5)	<1-58	92
Oil soot	13	4-106	107
Coal soot	30	6-66	52
Glassy fly ash	12	2-38	35
Biological Material	(24)	5-82	13
Pollen	35	13-39	15
Rubber	(43)	13-135	94

[a] Based on a total of 300 filters analyzed.

Pace *et al.* also analyzed data taken in other cities at different heights at the same sites. They concluded,[4] "roughly 12 to 20 $\mu g/m^3$ may be added to the concentrations at typical hi-volume sites due to the influence of nearby ground-level sources...."

Major open sources within the cities would include paved roads, unpaved roads, and construction. As Table 1.2 demonstrates, there are urban areas where the expected emissions from unpaved roads exceed those estimated to be emitted from "traditional" sources.

CONCLUSIONS

Emissions from unpaved roads greatly exceed those from point sources. In relatively dry regions of relatively high traffic density, they can be controlled for as little as $0.01/lb. Other open sources which rival point sources in magnitude are: construction emissions, wind erosion of cropland, and emissions from paved roads. Controlling such sources may be more cost-effective in reducing TSP concentrations than controlling point sources further. Whether such a strategy would also be optimal in a cost-benefit sense depends upon factors yet to be determined: transport of particulates and their relative toxicities, the value of increased life expectancy, the costs of alternative methods of saving lives.

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SECTION 2

DEFINING GOALS

INTRODUCTION

To set priorities, one first needs to identify one's goals. In air pollution control these are the reduction of air pollution damages in an economical and equitable manner. Because of the complexity of the source-transport-receptor-effects-valuation chain in air pollution control, often the criteria for choosing one approach over another represent rather imperfect surrogates for the optimally economic and equitable reduction of damage. This is discussed at greater length next.

DECISION FRAMEWORK

Figure 2.1 (from Deininger[1]) presents a general decision framework for decisions about control technology and regulations. This information would be required for determining whether the added cost of the controls/regulations was justified by the added benefits. Considerations of equity would also enter into such a decision. The major aspects of the decision framework are:

1. sources - emissions types, sizes, locations, future growth;
2. transport - concentrations created in time and space;
3. receptors - population magnitude and distribution;
4. effects - dose-response relationships;
5. impact - value and implications of effects and controls.

An approach to optimal control would be to use cost and benefit estimates for each alternative. Benefit estimation is quite difficult, however, and should involve equity considerations, which are unfortunately still subjective. A cost-effectiveness approach is less complete, but more tractable: this indicates the minimum cost to reach any particular set of conditions. For example, it could be determined what the minimum necessary cost was for achieving the National Ambient Air Quality Standards for a city like New York through a linear programming analysis.[1] Another cost-effectiveness example would be the determination of the maximum reduction of unpaved road emissions which could be obtained for one (or several) level(s) of expenditure; this we have done in Section 5.

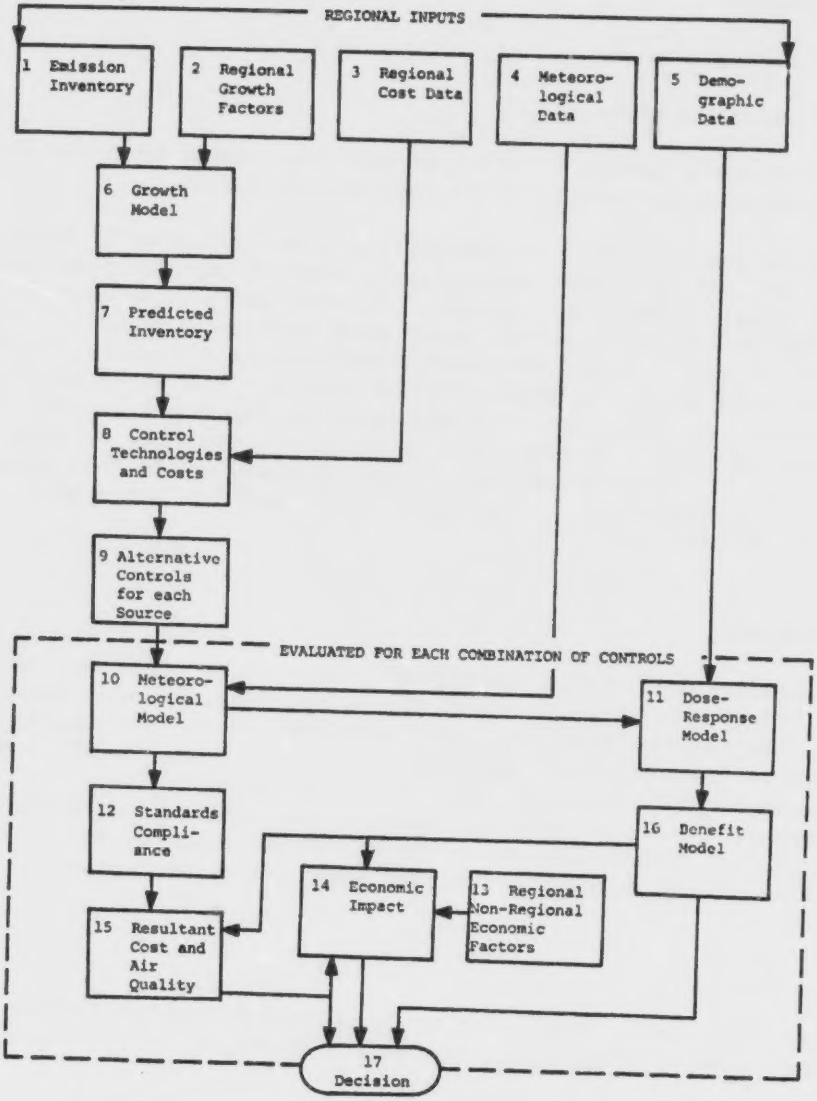
REGIONAL INPUTS
1 Emission Inventory
2 Regional Growth Factors
3 Regional Cost Data
4 Meteoro-logical Data
5 Demo-graphic Data
6 Growth Model
7 Predicted Inventory
8 Control Technologies and Costs
9 Alternative Controls for each Source
EVALUATED FOR EACH COMBINATION OF CONTROLS
10 Meteoro-logical Model
11 Dose-Response Model
12 Standards Compli-ance
16 Benefit Model
14 Economic Impact
13 Regional Non-Regional Economic Factors
15 Resultant Cost and Air Quality
17 Decision

Figure 2.1. General decision framework for air pollution control.[1]

Ideally, then, we would like information about the reduction of damages from various policies. Short of that we would prefer, in descending order:

-reduction of doses

-reduction of concentrations

-reduction of emission rates.

The cost-effectiveness approach, which we use here, would then ask for the maximum reduction achievable at various expenditures.

The sources and the costs of controlling them vary greatly geographically. It may be much more cost-effective to control unpaved road emissions in one region than another, for example. In some sense, the more detailed information we could provide about open sources, the better for those who have to make control decisions, but this is offset by information limitations as well as by the financial and manpower resources available for this project. We have chosen to aggregate to the state level; the states have primary responsibility in pollution control, so that those making the decisions based partly upon information in this document may well have responsibility at the state level, and the state-wide figures may be of most use.

CONCLUDING REMARKS

This investigation of the setting of priorities in open source control has led to the identification, state by state, of open sources contributing most to the total emission emission rate of the state. Further analysis is required to approximate the costs and benefits of control to make an optimal decision. For the overwhelmingly largest of these emitters, unpaved roads, we have performed a cost-effectiveness analysis (Section 5) to set priorities among the states for control and to serve as an illustration of the cost-effectiveness approach we recommend.

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SECTION 3

PROBLEM IDENTIFICATION

INTRODUCTION

One approach to systematic problem solving involves determination of goals, identification of problems, specification of criteria, evaluation of alternatives, implementation of the alternative selected, and monitoring of the performance of that alternative. This section is directed to characterizing some aspects of the problem of open sources of particulate emissions.

Three elements of air pollution are the sources, the transport of the material, and the effects on receptors. An optimizing approach to air pollution control would involve minimizing the effects (weighted for value) at a given budgetary level, or --- better yet --- continuing to add to control until the marginal cost of additional control just matched the marginal benefits of that control. Because of the complexity of evaluation of dose-response relationships and even of predicting dose given the sources, the approach taken in this study has been to focus on reduction of the emissions rather than reduction of the concentrations, the effects, or the cost of the effects.

We do not think that priorities for pollution control should be set solely on the basis of emission rates. Information on control costs and benefits and other impacts is clearly needed. However, to decide on which of the open sources we should first gather such additional information, we were strongly influenced by the dominant emission rate from unpaved roads, so that our cost-effectiveness investigation focused on this source.

We have divided emissions into those which are particularly harmful ("toxic") and those which are not particularly harmful, though not necessarily harmless. Industrial hygienists, for example, distinguish between "nuisance dusts" and those that are more toxic. We have adhered to the same distinction. Toxic substances are discussed in Appendix D. In this section, we deal with emissions which are not especially toxic, akin to "nuisance dusts" though not necessarily synonymous with them.

Emission rates are the masses of material emitted per period of time. Emission factors give the emission rates per unit of source extent. The determination of emission factors and source extents done for this study is described in Appendices A and F, and more information will be made available on request. This section presents emission rates by state for the major anthropogenic open sources of particulate emissions.

EMISSION FACTORS

The derivation of these is outlined in Appendix A, and they are presented by state in Table 1 of that appendix.

SOURCE EXTENTS

These, too, are explained in Appendix A; they are listed in Table 2 of that appendix.

EMISSION RATES

In Table 1.1 are presented the emission rate totals for the major open sources we identified. A partial listing of the state-by state emission rates appears in Table 3 of Appendix A. The general categories are: agriculture, construction, fires, mineral industries, and roads. As indicated in Table 1.1, unpaved road emissions were an order of magnitude larger than those from any other source, but the estimation of their magnitude is quite difficult (see Appendix A), thus suspect. Next largest were the rates from agriculture and from construction, followed by emissions from paved roads, wild fires, and the extraction of minerals. Relatively small contributions came from mineral tailings piles and from prescribed burning.

The national totals are less useful for control implementation than are the state totals, on which we concentrate in this section. The Clean Air Act of 1970 requires the states to develop State Implementation Plans to meet the National Ambient Air Quality Standards for criteria pollutants, including "total suspended particulates" (TSP). Therefore, much of the control decision-making takes place at the state level. Furthermore, as will be seen, the states differ greatly one from another, so that a major source in one state may well be minor in another.

To facilitate the presentation of the emission rate estimates by computer, we present in Table 3.1 an explanation of the lables used in the four succeeding tables. The emission estimates are for the masses of particulates smaller than about 30 μm in diameter and of specific gravity 2.5, which is equivalent to particles smaller than about 48 μm in aerodynamic diameter. Although these are thought to be the correct criteria for describing particles captured in the standard Hi-Vol used for measuring total suspended particulates, only particles smaller than about 10 μm aerodynamic diameter are respirable and capable of being transported miles or more under usual atmospheric conditions. Thus, a substantial portion of the mass of particulates emitted by open sources as indicated in these tables may not make an important contribution to the hazards of air pollution or even to the measures of total suspended particulates miles away from where they are generated.

Table 3.2 gives the emission rates for tilling, wind erosion, construction, wild fires, and prescribed fires. Table 3.3 continues these

TABLE 3.1. TERMS USED IN TABLES 3.2 to 3.6

AREA: State area, land and water, in thousands of square miles.

CONSTRUCTION: Emissions due to construction activities.[a]

EXTRACTION: Emissions from overburden removed to facilitate surface mining.

NON-ROAD: TOTAL minus the sum of PAVED and UNPAVED ROADS; in other words, the non-transportation contribution.

PAVED ROADS: Emissions from transportation over paved roads, due to re-entrainment of surface dirt.

POPULATION: State population, in millions.

PRESCRIBED FIRES: Emissions due to fires set for agricultural or silvacultural reasons.

TAILINGS: Emissions due to the re-entrainment of dust from tailings piles.

TILLING: Emissions due to tilling cropland.

TOTAL: Sum of the emission rate estimates from all major anthropogenic open sources of particulates.

UNPAVED ROADS: Emissions due to transportation over, and wind erosion of, unpaved roads due to re-entrainment of surface material.

WIND EROSION: Emissions due to wind erosion of cropland.

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[a] Note: all emission rates are in thousands of tons per year (909 x 10^3 kg per year).

TABLE 3.2. STATE EMISSION RATES: TILLING, WIND EROSION, CONSTRUCTION, WILD FIRES AND PRESCRIBED FIRES

State	Tilling	Wind Erosion	Construction	Wild Fires	Prescribed Fires
AL	5.30	47.5	273.	102.00	15.60
AK	0.10	0.0	59.	646.80	0.00
AZ	117.00	713.1	139.	28.50	5.20
AR	14.60	159.3	141.	94.50	4.10
CA	126.00	3945.8	4854.	218.80	21.20
CO	158.00	881.6	117.	25.00	0.50
CT	0.50	4.1	333.	1.00	0.00
DE	0.60	8.6	10.	0.05	0.04
FL	5.00	92.2	766.	316.60	71.90
GA	8.45	91.5	455.	41.30	54.30
HI	2.30	0.0	62.	0.00	0.00
ID	88.80	987.8	24.	544.00	45.40
IL	151.00	1721.4	1415.	11.40	0.00
IN	52.40	842.6	773.	8.90	0.00
IA	142.00	2077.7	253.	1.90	0.00
KS	239.00	4769.0	245.	65.80	0.00
KY	15.10	122.1	270.	62.50	0.00
LA	14.40	90.7	870.	73.00	16.60
ME	1.20	10.4	87.	2.50	0.00
MD	2.10	44.6	128.	1.40	0.00
MA	0.50	6.4	1260.	8.40	0.00
MI	21.20	410.7	743.	7.70	0.30
MN	99.30	1610.6	452.	30.80	0.00
MS	12.90	71.9	138.	78.60	12.70
MO	61.70	858.8	346.	119.80	0.00
MT	200.00	1264.1	31.	99.60	52.90
NE	306.00	5218.9	197.	20.00	0.00
NV	68.00	1157.1	22.	14.80	0.00
NH	0.40	0.5	69.	0.46	0.00
NJ	1.60	15.7	844.	23.50	1.50
NM	50.30	842.3	61.	19.90	1.40
NY	20.10	149.6	1462.	6.00	0.00
NC	6.30	118.2	640.	75.10	8.80
ND	292.00	3553.3	80.	0 47	0.10
OH	44.20	822.8	1365.	5.20	0.00
OK	89.00	1177.9	332.	115.80	0.00
OR	39.40	48.2	212.	196.50	21.60
PA	21.60	81.6	2090.	12.90	0.00
RI	0.10	0.9	82.	0.70	0.00
SC	4.30	54.0	177.	43.60	29.10
SD	210.00	3119.6	39.	4.80	0.00
TN	10.90	41.2	333.	27.70	0.00
TX	386.00	5000.7	3760.	19.10	6.20
UT	78.40	653.4	203.	10.00	0.00
VT	1.90	8.1	17.	0.20	0.00
VA	5.30	71.0	212.	5.60	3.90
WA	14.60	64.3	447.	164.30	56.80
WV	2.84	5.6	215.	74.20	0.00
WI	49.00	663.1	218.	6.90	0.00
WY	56.30	638.8	59.	8.30	0.00

TABLE 3.3. STATE EMISSION RATES: MINERAL EXTRACTION: COAL AND OTHER, TAILINGS, PAVED AND UNPAVED ROADS

State	Extraction: Coal	Extraction: Other	Tailings	Paved Roads	Unpaved Roads
AL	16.9	39.3	1.1	149.	3760.
AK	0.6	127.0	0.0	11.	1990.
AZ	0.2	187.0	156.7	92.	9740.
AR	0.4	38.0	1.0	73.	9340.
CA	0.0	171.0	141.5	803.	27530.
CO	0.2	33.8	17.0	89.	10080.
CT	0.0	15.1	0.4	117.	320.
DE	0.0	2.4	0.0	23.	70.
FL	0.0	235.0	2.6	386.	7010.
GA	0.0	54.6	1.3	212.	7010.
HI	0.0	9.0	0.0	26.	80.
ID	0.0	17.8	30.9	30.	4120.
IL	49.5	104.0	5.5	370.	7960.
IN	20.2	58.1	2.6	229.	6450.
IA	0.5	49.4	4.8	104.	11310.
KS	0.6	28.5	22.5	78.	14330.
KY	116.6	36.6	2.1	146.	4380.
LA	0.0	24.5	0.4	121.	3790.
ME	0.0	5.4	0.2	43.	710.
MD	2.0	30.5	0.8	154.	710.
MA	0.0	25.7	0.5	182.	680.
MI	0.0	139.0	6.7	345.	8830.
MN	0.0	216.0	20.4	139.	11560.
MS	0.0	18.2	0.2	81.	4260.
MO	3.9	56.1	19.3	175.	10330
MT	0.4	33.9	11.6	28.	773.
NE	0.0	16.9	2.8	56.	10610.
NV	0.0	36.8	142.2	21.	4890.
NH	0.0	6.8	0.0	32.	1250.
NJ	0.0	44.9	1.8	304.	1950.
NM	0.3	42.5	44.0	48.	10640.
NY	0.0	75.6	10.0	414.	5160.
NC	0.0	57.1	2.0	220.	3860.
ND	0.0	5.1	1.5	17.	8800.
OH	38.6	95.9	6.3	403.	3820.
OK	2.0	32.0	6.5	123.	11860.
OR	0.0	45.0	1.4	83.	12110.
PA	68.4	90.7	4.0	424.	10100.
RI	0.0	3.2	0.1	36.	390.
SC	0.0	24.3	0.6	126.	1350.
SD	0.0	12.4	5.3	24.	6370.
TN	6.4	56.0	1.5	191.	4380.
TX	0.0	116.0	25.9	476.	28640.
UT	0.2	55.8	118.0	42.	5410.
VT	0.0	5.3	0.7	18.	1180.
VA	29.2	58.7	3.9	214.	2340.
WA	0.1	38.1	0.7	137.	6710.
WV	87.1	14.6	1.2	60.	3920.
WI	0.0	53.9	2.9	176.	3310.
WY	0.6	17.9	5.9	19.	2440.

TABLE 3.4. STATE EMISSION RATES: TOTAL OPEN SOURCE EMISSIONS AND TOTAL NON-ROAD OPEN SOURCE EMISSIONS

States	Total	Non-Road
AL	4409.7	500.70
AK	2834.5	833.50
AZ	11178.7	1346.70
AR	9865.9	452.90
CA	37811.3	9478.30
CO	11402.1	1233.10
CT	791.1	354.10
DE	114.7	21.69
FL	8885.3	1489.30
GA	7928.4	706.45
HI	179.3	73.30
ID	5888.7	1738.70
IL	11787.8	3457.80
IN	8436.8	1757.80
IA	13943.3	2529.30
KS	19778.4	5370.40
KY	5151.0	625.00
LA	5000.6	1089.60
ME	859.7	106.70
MD	1073.4	209.40
MA	2163.5	1301.50
MI	10503.6	1328.60
MN	14128.1	2429.10
MS	4773.5	332.50
MO	11970.6	1465.60
MT	2494.5	1693.50
NE	16427.6	5761.60
NV	6351.9	1440.90
NH	1359.2	77.16
NJ	3187.0	933.00
NM	11749.7	1061.70
NY	7297.3	1723.30
NC	4987.5	907.50
ND	12749.5	3932.47
OH	6601.0	2378.00
OK	13738.2	1755.20
OR	12757.1	564.10
PA	12893.2	2369.20
RI	513.0	87.00
SC	1808.9	332.90
SD	9785.1	3391.10
TN	5047.7	476.70
TX	38429.9	9313.90
UT	6570.8	1118.80
VT	1231.2	33.20
VA	2943.6	389.60
WA	7632.9	785.90
WV	4380.5	400.54
WI	4479.8	993.80
WY	3245.8	786.80

TABLE 3.5. STATE POPULATIONS, AREAS, EMISSION RATES: TOTAL PER AREA, NON-ROAD PER AREA, TOTAL PER POPULATION, NON-ROAD PER POPULATION

STATES	POPULATION	AREA	TOTAL PER AREA	NON-ROAD PER AREA	TOTAL PER POPULATION	NON-ROAD PER POPULATION
AL	3.44	51.600	85.459	9.703	1281.9	145.55
AK	0.30	586.000	4.837	1.422	9448.3	2778.33
AZ	1.77	114.000	98.059	11.813	6315.6	760.85
AR	1.92	53.100	185.799	8.529	5138.5	235.89
CA	19.95	159.000	237.807	59.612	1895.3	475.10
CO	2.21	104.000	109.636	11.857	5159.3	557.96
CT	3.03	5.010	157.904	70.679	261.1	116.86
DE	0.55	2.060	55.675	10.529	208.5	39.44
FL	6.79	58.600	151.626	25.415	1308.6	219.34
GA	4.59	58.900	134.609	11.994	1727.3	153.91
HI	0.77	6.450	27.798	11.364	232.9	95.19
ID	0.71	83.600	70.439	20.798	8293.9	2448.87
IL	11.11	56.400	209.004	61.309	1061.0	311.23
IN	5.19	36.300	232.419	48.424	1625.6	338.69
IA	2.83	56.300	247.661	44.925	4927.0	893.75
KS	2.25	82.200	240.613	65.333	8790.4	2386.84
KY	3.22	40.400	127.500	15.470	1599.7	194.10
LA	3.64	48.500	103.105	22.466	1373.8	299.34
ME	0.99	33.200	25.895	3.214	868.4	107.78
MD	3.92	10.600	101.264	19.755	273.8	53.42
MA	5.69	8.260	261.925	157.567	380.2	228.73
MI	8.88	58.200	180.474	22.828	1182.8	149.62
MN	3.81	84.100	167.992	28.883	3708.2	637.56
MS	2.22	47.700	100.073	6.971	2150.2	149.77
MO	4.68	69.700	171.745	21.027	2557.8	313.16
MT	0.69	147.000	16.969	11.520	3615.2	2454.35
NE	1.48	77.200	212.793	74.632	11099.7	3892.97
NV	0.49	111.000	57.224	12.981	12963.1	2940.61
NH	0.74	9.300	146.146	8.297	1836.7	104.27
NJ	7.17	7.840	406.505	119.005	444.5	130.13
NM	1.02	122.000	96.309	8.702	11519.3	1040.88
NY	18.24	49.600	147.123	34.744	400.1	94.48
NC	5.08	52.600	94.819	17.253	981.8	178.64
ND	0.62	70.700	180.332	55.622	20563.7	6342.69
OH	10.65	41.200	160.218	57.718	619.8	223.29
OK	2.56	69.900	196.541	25.110	5366.5	685.63
OR	2.09	97.000	131.516	5.815	6103.9	269.90
PA	11.79	45.300	284.618	52.300	1093.6	200.95
RI	0.95	1.210	423.967	71.901	540.0	91.58
SC	2.51	31.100	58.164	10.704	720.7	132.63
SD	0.67	77.000	127.079	44.040	14604.6	5061.34
TN	3.92	42.200	119.614	11.296	1287.7	121.61
TX	11.20	267.000	143.932	34.884	3431.2	831.60
UT	1.06	84.900	77.395	13.178	6198.9	1055.47
VT	0.44	9.610	128.117	3.455	2798.2	75.45
VA	4.65	40.800	72.147	9.549	633.0	83.78
WA	3.41	68.200	111.919	11.523	2238.4	230.47
WV	1.74	24.200	181.014	16.551	2517.6	230.20
WI	4.42	56.200	79.712	17.683	1013.5	224.84
WY	0.33	97.900	33.154	8.037	9835.8	2384.24

emission rate estimates for mineral extraction and beneficiation (mill tailings) and for roads (paved and unpaved, including wind erosion of unpaved roads).

Table 3.4 presents the total anthropogenic open source emission rates of particulates and the non-road contribution to that total. Table 3.5 presents the 1970 populations of the states, their total areas, and emissions per population and per area. The material in Tables 3.2-3.5 is discussed next.

Total Emissions

Total emissions by state ranged from 115 thousand tons per year (Delaware) to 38,400 thousand tons per year (Texas), with the median value being 6,460. Figure 3.1 shows the histogram derived from these data. The intervals are 1000 thousand tons per year. Note that Texas and California together contribute 19 percent of the total emissions.

Emissions per area (tons per square mile per year) is another useful measure. If one were to formulate a simple box model for the air above the state, the concentrations would be proportional to the rate of emissions per area (of material which stayed suspended). These values ranged from 4.8 to 424 tons/sq. mi./yr. A measure of the relative dispersion of the values is the coefficient of variation (COV), the standard deviation divided by the mean. For the state total emissions, the COV was 0.95. If a major factor in the emissions were the area of the state, we would expect that total emissions per area would have a smaller COV, which it does, 0.60. The comparative coefficients of variation show that the states are more alike in their emissions per area than they are in their total emissions, not unsurprisingly. Figure 3.2 is a histogram of total emissions per area. The two largest values are for Rhode Island and New Jersey.

States differ greatly in population. Emissions per person indicate not only something about the relative contribution of individuals between states to the air pollution problem, but also the relative doses, to the degree to which concentrations correlate with emission rates. Figure 3.3 shows a histogram of emissions per population, which range from 208 to 20,500 tons/year/thousand, with a mean value of 3,884. The COV is 1.14. The three highest states are North Dakota, South Dakota, and Nevada, principally due to their unpaved road emissions and relatively small populations.

On a state-by-state basis, as well as on an aggregated national basis, the dominant contributor to our emission rate estimates is unpaved road emissions. Figure 3.4 shows total emissions versus unpaved road emissions, for the states. The correlation is evident; in fact, the correlation coefficient is $r=0.99$ and the coefficient of determination is $r^2=0.98$, indicating that 98 percent of the state-to-state variation can be "explained" by the variation in unpaved road emissions. The regression equation is

$$c12 = -107 + 1.30\ c10$$

where

c12 = total state open source emissions, 10^3 tons/yr

```
middle of    number of
interval     observations
   1000.          9     *********
   3000.          6     ******
   5000.          9     *********
   7000.          6     ******
   9000.          4     ****
  11000.          6     ******
  13000.          5     *****
  15000.          1     *
  17000.          1     *
  19000.          1     *
  21000.          0
  23000.          0
  25000.          0
  27000.          0
  29000.          0
  31000.          0
  33000.          0
  35000.          0
  37000.          1     *
  39000.          1     *
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Figure 3.1. Histogram: total emissions.

```
middle of   number of
interval    observations
     10.        2     **
     30.        3     ***
     50.        3     ***
     70.        4     ****
     90.        4     ****
    110.        6     ******
    130.        5     *****
    150.        5     *****
    170.        3     ***
    190.        5     *****
    210.        2     **
    230.        2     **
    250.        2     **
    270.        1     *
    290.        1     *
    310.        0
    330.        0
    350.        0
    370.        0
    390.        0
    410.        1     *
    430.        1     *
```

Figure 3.2. Histogram of state total emissions per area.

```
middle of   number of
interval    observations
    500.      13    *************
   1500.      13    *************
   2500.       5    *****
   3500.       3    ***
   4500.       1    *
   5500.       3    ***
   6500.       3    ***
   7500.       0
   8500.       2    **
   9500.       2    **
  10500.       0
  11500.       2    **
  12500.       1    *
  13500.       0
  14500.       1    *
  15500.       0
  16500.       0
  17500.       0
  18500.       0
  19500.       0
  20500.       1    *
```

Figure 3.3. Histogram of state total emissions per population.

```
     c12
40000.+
      -                                   * *
      -
      -
      -
30000.+
      -
      -
      -
      -
20000.+                   *
      -
      -              *
      -               2*
      -           ***4 *
10000.+         *  **
      -       * 22
      -      5**
      -   ***4
      -  43*
    0.+ 4*
        +---------+---------+---------+---------+---------+c10
       0.              16000.              32000.
              8000.              24000.              40000.
```

Figure 3.4. Total emissions by state (c12) versus unpaved road emissions (c10).

c10 = state unpaved road emissions, 10^3 tons/yr.

The intercept is not statistically significantly different from 0.0. Not only are unpaved roads the dominant source, but they tend to increase in rate when agricultural tilling and wind erosion increase, due to the climatic determinants the emission factors have in common. (See Appendix E.)

Paved roads also contribute substantially. The correlation coefficient for total emissions versus paved road emissions is $r = 0.58$. In turn, paved road emissions are strongly correlated with population ($r = 0.95$). Note that population and the emission rates for construction ($r = 0.86$) and unpaved roads ($r = 0.48$) have high correlation coefficient values. For example, $r^2 \geq 0.25$ means that the influence of population "explains" at least 25 percent of the variation among the states. A predictive linear equation for total emissions based just upon population and area accounted for 45 percent of the variation among the states ($r^2 = 0.37$).

Thus, unpaved roads are the dominant contribution to state emission rates, as estimated here. Along with paved roads, they contribute 84 percent of the estimated total emissions.

Non-Road Total Emissions

There is value in separating the total into transportation and non-transportation contributions. For one thing, if the emission rate estimates for unpaved roads are later shown to be greatly in error, the non-road estimates here would not be affected. Agricultural emissions, construction emissions, fires, and emissions from the mineral industries all are related to climatic conditions, although the relations differ. Where measures to reduce transportation emissions are infeasible, proposals for action might center on this broad group.

Figure 3.5 is a histogram of non-road emissions. They range from 21 to 9478 thousand tons per year, with a median of 1075 and a coefficient of variation of 1.23. These values and the histogram show that the emissions rates have great variation. In decreasing order, the states with the largest non-road rates are: California, Texas, Illinois, and Nebraska. In these states, the contributions are primarily from wind erosion of cropland and from construction. Accounting for irrigation would substantially lessen the California rate (Appendix F).

Wind erosion, the second largest source, is highly correlated with non-road emissions. We regressed the non-road emission rates (c15) versus the wind erosion emission rates (c4). The slope and the intercept of the following regression equation were both statistically significant ($P < 0.05$):

$$c15 = 488 + 1.32\ c3$$

where

c15 = non-road emissions rates, 10^3 tons/yr
c3 = wind erosion emissions rates, 10^3 tons/yr

```
middle of   number of
interval    observations
   250.       14     **************
   750.       10     **********
  1250.       10     **********
  1750.        5     *****
  2250.        3     ***
  2750.        1     *
  3250.        2     **
  3750.        1     *
  4250.        0
  4750.        0
  5250.        1     *
  5750.        1     *
  6250.        0
  6750.        0
  7250.        0
  7750.        0
  8250.        0
  8750.        0
  9250.        2     **
```

Figure 3.5. Histogram of state non-road emissions rates.

The correlation coefficient was r = 0.81. It is this high partly because wind erosion emissions contribute heavily to the non-road emissions, partly because they covary with other important emissions.

The non-road emission rates are better correlated with the simple measures of extent, state area and state population, than were the total emission rates. For the non-road sources the regression equation for total emissions:

$$c15 = 154 + 241\ c13 + 7.33\ c14$$

where

c13 = state population, millions
c14 = state area, millions of square miles,

had a coefficient of determination $r^2 = 0.37$ (meaning it accounted for 76 percent of the variation). The intercept and the slopes were all statistically significant with the population being the most significant.

Having looked at the totals and the non-transportation totals, we next examine briefly the individual emission rates.

Agricultural Tilling

These rates depend primarily on soil type, climatic conditions, and acres of cropland harvested yearly. The five states with the largest emission rates (in decreasing order) are: Texas, Nebraska, North Dakota, Kansas, and South Dakota. The two states with the smallest are Alaska and Rhode Island.

Wind Erosion of Cropland

Wind erosion depends upon soil type, climatic factors, crop type and crop acreage, among other factors. The states with the five largest emission rates are (decreasing order): Nebraska, Texas, Kansas, California, and North Dakota. Accounting for irrigation would substantially reduce the rates for California (Appendix F).

Construction

These emissions were estimated from very approximate emission factors for the states, adjusted for type of construction, with source extents taken from construction activity types and expenditures. The top five state rates were (decreasing order): California, Texas, Pennsylvania, New York, and Illinois. The two smallest: Vermont and Delaware.

Paved Roads

As noted above, paved road emissions were very highly correlated with population. Thus the top five states are about as expected: California, Texas, Pennsylvania, New York, and Ohio. The rate for New York, the second most populous state, would be expected to be higher; Figure 3.5 shows paved road emission rates by state versus population, and it can be seen that New York's value lies well below the trend. This suggests there is relatively less driving per capita there than in most other states, due to demographic and socio-economic factors. The states with the least paved road emissions were Alaska and North Dakota.

Unpaved Roads

Texas produced only slightly more unpaved road emissions by our estimates than did California, followed by Kansas, Oregon, and Oklahoma. The least were produced by Delaware and Hawaii.

Wild Fires

The top five states are: Alaska, Indiana, Florida, California, and Oregon. The smallest two are Vermont and Delaware.

Prescribed Fires

The biggest five emission rate estimates were for: Florida, Washington, Georgia, Missouri, and Indiana; many states had negligible rates.

Minerals: Coal

Kentucky is estimated to have the greatest emissions rate due to coal mining, followed by West Virginia, Pennsylvania, Illinois, and Ohio. Many states had negligible coal mining emissions.

Minerals: Other Than Coal

Phosphate rock extraction helped make Florida the leader in this emission rate category, with the next highest being Minnesota (iron ore), then Arizona, California, and Michigan. The smallest are Rhode Island and Delaware.

Minerals: Tailings

The biggest five are: Arizona, Nevada, California, Utah, and New Mexico, all in the Southwest. The smallest two are Rhode Island and Maine.

Correlation Matrix

Table 3.6 contains all the correlation coefficients for the various possible combinations of emission rates. The first column is a list of the variables. The first row contains a similar list. The rest of the table gives the correlation coefficients. The first column of numbers has correlation coefficient values for the emission rates, etc., versus the "state numbers," the alphabetical rank of the state (Alabama=1, Wyoming=50). These state numbers should be essentially randomly associated with any of the other variables, but one of the numbers in the first column of coefficients would be significant at $P<0.05$ ($r>0.28$), which shows that if you test enough random

TABLE 3.6. MATRIX OF CORRELATION COEFFICIENTS

	State No.	Tilling	Wind Erosion	Construction	Wild Fires	Prescribed Fires
Tilling	0.053					
Wind Erosion	0.012	0.922				
Construction	-0.039	0.267	0.394			
Wild Fires	-0.319	-0.085	-0.055	0.022		
Prescribed Fires	-0.130	-0.059	-0.106	0.049	0.458	
Extraction: Coal	0.096	-0.137	-0.140	0.099	-0.080	-0.168
Extraction: Other	-0.257	0.083	0.123	0.469	0.271	0.217
Paved Roads	-0.067	0.056	0.192	0.889	0.001	0.131
Unpaved Roads	-0.067	0.630	0.707	0.688	0.072	0.029
Tailings	-0.139	0.203	0.246	0.275	0.035	-0.023
Total	-0.061	0.686	0.775	0.735	0.066	0.022
Population	-0.040	0.052	0.173	0.855	-0.051	0.029
Area	-0.169	0.286	0.254	0.186	0.643	0.049
Non-Road	-0.036	0.792	0.901	0.746	0.042	-0.012
Total per Area	0.037	0.098	0.208	0.325	-0.220	-0.200
Non-Road per Area	-0.044	0.205	0.301	0.351	-0.191	-0.199
Total per Population	0.093	0.578	0.531	-0.251	0.158	-0.109
Non-Road per Population	0.086	0.654	0.609	-0.185	0.161	-0.043

TABLE 3.6. (cont'd)

	Extraction: Coal	Extraction: Other	Paved Roads	Unpaved Roads	Tailings	Total
Extraction: Other	0.008					
Paved Roads	0.167	0.593				
Unpaved Roads	-0.053	0.468	0.542			
Tailings	-0.135	0.367	0.164	0.386		
Total	-0.051	0.458	0.575	0.989	0.382	
Population	0.170	0.517	0.953	0.478	0.137	0.517
Area	-0.134	0.360	0.028	0.322	0.207	0.329
Non-Road	-0.055	0.349	0.551	0.841	0.328	0.910
Total per Area	0.133	0.077	0.354	0.259	-0.095	0.276
Non-Road per Area	0.012	0.004	0.309	0.089	-0.066	0.167
Total per Population	-0.202	-0.131	-0.423	0.229	0.269	0.239
Non-Road per Population	-0.179	-0.157	-0.349	0.121	0.135	0.181

TABLE 3.6. (cont'd)

	Population	Area	Non-Road	Total Per Area	Non-Road Per Area	Total Per Population
Area	0.010					
Non-Road	0.516	0.322				
Total Per Area	0.354	-0.291	0.277			
Non-Road Per Area	0.340	-0.197	0.356	0.748		
Total Per Population	-0.401	0.366	0.285	-0.133	-0.044	
Non-Road Per Population	-0.318	0.347	0.369	-0.109	0.105	0.909

correlations, chance will produce some "significant" ones. In the remainder of the table, correlation coefficients greater than $r = 0.5$ have been underlined, not because they are statistically significant (though they are, at $P < 0.01$), but because the relationship is strong enough that it "explains" 25 percent or more of the variation in the two variates compared.

Inspecting the matrix, we find the following to have high correlations ($r \geq 0.5$):

1. Agricultural tilling emissions and: emissions from wind erosion, unpaved roads, total emissions, total per population, non-road and non-road per population.
2. Wind erosion emissions and: emissions from tilling, unpaved roads, total emissions, non-road emissions.
3. Construction emissions and: emissions from paved roads, from unpaved roads, total emissions, total per population, non-road, and non-road per population.
4. Wild fires and area.
5. Prescribed fires and none.
6. Coal extraction emissions and none.
7. Emissions from extraction of minerals other than coal and: emissions from paved roads, total emissions, and population.
8. Paved road emissions and: unpaved road emissions, total and non-road emissions, and population (as well, of course, as those named above: wind erosion, construction, and mineral extraction other than coal.)
9. Unpaved road emissions and: emissions from tilling, wind erosion, construction, paved roads, non-road emissions, and total emissions.
10. Mineral tailings and none.
11. Total emissions and: agricultural tilling, wind erosion of cropland, construction, mineral extraction other than coal, both paved and unpaved roads, population, and non-road emissions.
12. Non-road emissions and: all the same factors as for total emissions, except for wind erosion of cropland.
13. Population and: wind erosion of cropland, construction, paved and unpaved road emissions, and non-road and total emisssions.
14. Area and: wild fires.
15. Non-road total and: wind erosion of cropland, construction, paved and unpaved road emissions,tailings, and total emissions.

The large number of correlations and the fact that all those having $r = 0.50$ or larger are positive indicate that states with one open source emission problem have others as well.

CONCLUDING REMARKS

The state-by-state emission rate estimates presented here can be useful in setting priorities for control. Many of the emissions are correlated with other emissions as well, suggesting that those states with any open sources problem probably have several. The major emission sources were generally unpaved roads, wind erosion of cropland, construction, and paved roads.

SECTION 4

FIGURES OF MERIT

INTRODUCTION

Particles impair health, increase rates of weathering and corrosion of materials, contribute to the damage of vegetation, and decrease visibility. The decision to control open sources of emissions, and the selection of a strategy of control, affect society in two ways: the amount, type, and location of damage done by particles is altered, and resources are diverted from other uses to control open sources of emissions. In an ideal world, the optimal level of control would be easily determined. Control expenditures would be increased to the point at which the marginal social benefit (associated with emission reductions) was exactly equal to the marginal social cost (of reducing emissions). In this ideal world costs and benefits would be measured in units of social welfare, i.e., the system of measurement would incorporate simultaneous consideration of equity and economic efficiency. In the real world imperfect information prevents us from knowing how close our actual decisions are to these optimal decisions, and even with such information it might be impossible to achieve an ideal solution. Nonetheless, consideration of these abstract models may help us avoid grossly inefficient or inquitable social policies.

DOSE-RESPONSE RELATIONSHIPS

In order to develop an open source model useful in the selection of an optimal control policy, we would first consider the physical system's behavior, and later translate measures of physical performance into measures of social desirability. The elements of the physical system are: source, control system, transport system, and receptor. A control policy consists simply of the specification of which sources to control, the selection of a control method (and possibly, degree of control for each source requiring control)*.

---

*In a systems model we hope to relate measures of output (here, air pollution damages) to parameters of the system which we can vary (control system expenditures). To complete a systems model, it must be possible to mathematically describe the behavior of each component of the system.

As the value of any control policy is directly contingent upon reduction in physical damages to receptors, we feel that a brief discussion of the response of various receptors to particles is in order.†

As air is such a prevasive medium, it would be difficult to make a comprehensive listing of receptors. It is conceivable that certain organisms and/or materials benefit by the changes in air quality induced by man's activities. However, traditionally discussions of the "receptors" of "air pollution" have been limited to those materials and/or organisms which are thought to be adversely affected by air pollution, *e.g.*:

i. humans
ii. vegetation
iii. materials

Although a large number of crops (including potatoes, corn, tomatoes, green beans, lima beans, soy beans, grapes, oranges, tobacco, spinach, peanuts, and alfalfa) and many other plants are known to be injured by air pollution, oxidants (*e.g.*, ozone, nitrogen dioxide, and peroxyacetyl nitrate) and sulfur dioxide are most frequently implicated. Similarly, although Yocum and McCaldin[1] have identified damage to metals, building materials, paint, leather, paper, textiles, dyes, natural and synthetic rubber, glass, ceramics, and electrical equipment as a portion of the social costs of air pollution, sulfur dioxide, acid gases, and oxidants are the most frequently cited causes of damage.

In contrast, physiologists have identified three mechanisms by which exposure to particles could affect human health:

i. direct chemical or toxic action of the particle, *per se*; *e.g.*, arsenic, lead, beryllium;

ii. indirect effects which are mediated by the physical properties of the particle; *e.g.*, mucous flow, slowed ciliary beat, overloading macrophages, or penetration of the alveolar membrane;

iii. adsorption or absorption of gases or solutes, thereby increasing their effect by holding them more focally in the deeper portions of the lungs for longer periods of time.

Exposure to air pollution is thought to influence the rates of incidence and prevalence of disease, and to affect its severity. Asthma, emphysema, chronic bronchitis, respiratory infections, lung cancer, angina pectoris, arteriosclerosis, myocardial infarction, and conjunctivitis are diseases which are currently suspected of being induced (either directly, or indirectly by increasing susceptibility to a causal factor) or aggravated by community air pollutants. This increased incidence, prevalence, and severity of disease is thought to indirectly contribute to reductions in life expectancy.

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†Even if we were able to complete the physical systems model, a full social model would include evaluation of the social desirability of alternative policies. Currently there are both theoretical and practical limitations to attempts to place a value on reductions of mortality and morbidity, effects of great significance in any air pollution model.

Although much effort of epidemiologists, toxicologists, physicians, biochemists, and physiologists has been devoted to the analysis of these relationships, many questions remain largely unanswered. These would include:

i. At the levels of air pollution which currently prevail in the U.S., how much (if any) additional life shortening is produced by each incremental unit of air pollution exposure?

ii. Which pollutants are responsible for any reductions in life expectancy or increments in morbidity?

iii. Are the observed effects due to chronic exposure to annual mean levels of pollution, or are all effects due to the occasional periods of peak exposure?

Until these issues are clarified, we are left simply speculating about the appropriate form of weighted human dose function. A few hypothetical weighted human dose functions are outlined here simply to illustrate the wide range of intuitively attractive alternatives.

FORM 1: $D_T = \int_0^T C_{TSP}\, dt$

FORM 2: $D_T = \int_0^T C_{mrp}\, dt$

FORM 3: $D_T = \int_0^T [C_{mrp} - K_{mrp}]\, dt$

FORM 4: $D_T = \int_0^T [C_{TSP} - K_{mrp}]^P\, dt$

FORM 5: $D_T = a_{cd} \int_0^T [C_{cd} - K_{cd}]\, dt + a_{B\alpha P} \int_0^T [C_{B\alpha P} - K_{B\alpha P}]\, dt + \ldots$

where

D_T = dose received in the interval $t = 0$ to $t = T$.

C_{TSP} = concentration of total suspended particulates

C_{mrp} = concentration of mass respirable particulates

C_{cd} = concentration of cadmium

$C_{B\alpha P}$ = concentration of benzo-α-pyrene

P = an unspecified exponent

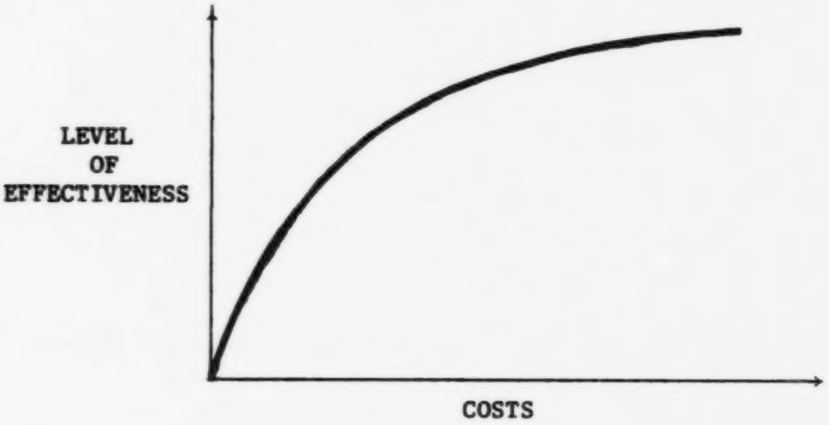
a = relative toxicity factor

K = a threshold for given pollutant

Clearly, more complex measures of dose (e.g., including synergisms and antagonisms, non-linear relationships with concentration) may be required to adequately reflect human physiological response to particles in the atmosphere.

COST-EFFECTIVENESS CRITERION

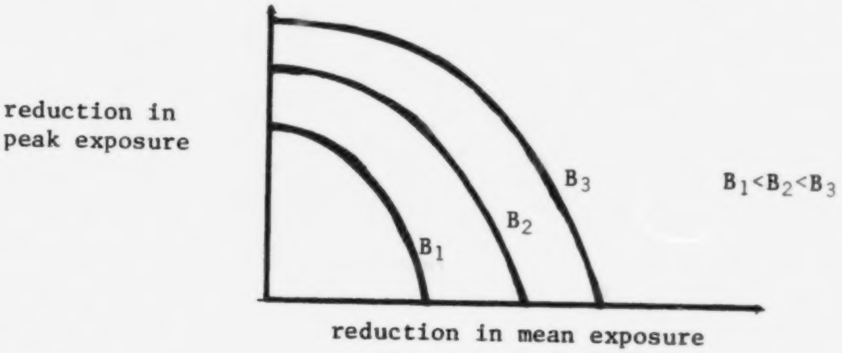
This uncertainty as to the response of the system to increased ambient concentrations of particles limits our ability to carry out a full cost-benefit analysis. We must be content with an analysis of the cost-effectiveness of alternative control strategies. In a cost-effectiveness analysis we seek to minimize the costs associated with achievement of a specified level of effectiveness. By combining several cost-effectiveness analyses, we can determine the minimum cost associated with any specified level of effectiveness. Alternatively stated, for any level of control expenditure we will know how to achieve the maximum level of effectiveness:



Many measures of effectiveness might be suggested: reduction of mean annual TSP concentrations, reduction of peak TSP concentrations, reduction of population-weighted TSP levels, reduction of inhalable particulate levels, reduction of respirable lead levels, reduction of asbestos emissions, reduction of frequency of exceeding a threshold TSP concentration, reduction of mass emissions of soil-like particles, reduction of emissions of particles with aerodynamic diameters less than 10 μm, or a weighted sum of these. In the selection of a criterion we balance two factors: the degree to which we believe the criterion is correlated with human response, and the amount of effort required to complete an analysis involving the criterion.* Relatively complex criteria are likely to be highly correlated with human response, but may require considerable computational efforts.

CONCLUSIONS

We recommend a sequential analysis of the open source problem. Attractive alternatives could be identified in a preliminary cost-effectiveness analysis using reduction of mass emissions of particles not significantly more toxic than soil as the criterion of efficiency.† In the second stage of analysis, promising alternatives could be more thoroughly investigated using a more sophisticated criterion, such as a weighted sum of reductions in population-weighted annual mean TSP exposures and peak TSP exposures. By allowing the weights to vary, a "production possibility frontier" could be sketched for each budgetary level (B_i):



In the following section, we apply the cost-effectiveness approach to the largest source of soil-like particles, reentrainment of road dust from unpaved roads.

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*In this balancing we must bear in mind that policies based on distant surrogates for human response may involve socially inefficient expenditures of control resources.

†This could be accompanied by a qualitative analysis of the feasibility of control and estimation of control costs for sources emitting potentially toxic particles, e.g., asbestos, lead, cadmium....

REFERENCES

1. Yocom, J. E. and R. O. McCaldin. Effects of Air Pollution on Materials and the Economy. In: Air Pollution, Stern, A. C. (ed.), Academic Press, Vol. 1 (2nd Ed.), 1968.

SECTION 5

EVALUATION OF CONTROL STRATEGIES: COST-EFFECTIVENESS OF THE CONTROL OF UNPAVED ROADS

INTRODUCTION

Dust arises from unpaved roads through three mechanisms: wind erosion of the unpaved surface, action of the tires, and surface disturbance by the aerodynamic wake behind the vehicle. Heinsohn, Birnie, and Cuscino[20] note that estimates of crude emission factors range from 0.04 to 55.9 pounds per vehicle mile and postulate that the extreme variability in these estimates stems from underlying variability in:

1. speed and shape of the vehicle,
2. physical characteristics of the road surface,
3. meteorological conditions,
4. size distribution of the aerosol, and
5. uncertainty in sampling and estimation methods.

By parameterizing the emission factor, uncertainty can be separated from true variation. The emission factor currently sanctioned by the EPA includes such parameterization:[1]

$$E_o = (0.60)(0.81)(S_r)(\frac{S}{30})(1 - \frac{w}{365})$$

where

E_o = emission factor (lbs/veh-mi)
S_r = road surface silt content (percentage $\leq$ 75 μm diameter)
S = average vehicle speed (mph)
w = number of days per year with $\geq$ .01 inch of rain, or snow cover.

Considering the wide fluctuations in climate and soil types across the nation, it should not be surprising that the average emission factors for states vary from 3.9 pounds per vehicle mile in South Carolina to 13.2 pounds per vehicle mile in California.[2]

Generic methods of pollution control include alteration of the source, the transport mechanism or the receptor. In air pollution control, efforts have been concentrated on source control. Open source control is no exception. Widely-used methods of road dust control include paving, oiling, watering, and the application of calcium chloride. Speed reduction is often suggested as an emission control method, since emission factors increase at least proportionally with vehicle speed. Although many methods of chemical stabilization have been tested (and appear to be more effective than oiling), not enough data is available to permit evaluation of their cost efficiency. Briefly, we summarize the estimates of control cost and efficiency for each of the feasible control methods below.

CONTROL COSTS AND EFFICIENCIES

Paving

The term "paving" is very ambiguous. Paved surfaces vary from what is referred to by the industry as a "single chip seal" to portland cement surfaces over several inches of bituminous material. The costs of paving and the life of the paved surface will clearly depend not only upon the surface type, but also on the condition of the existing surface, traffic density, severity of climate, and regional costs of aggregate and labor. The estimates of initial cost and expected surface life which we have compiled are presented in Table 5.1. In order to facilitate comparison of these cost estimates we have inflated capital costs to equivalent mid-1977 levels using the "bituminous surface cost index," and have made similar adjustments in the annual operations and maintenance figures on the basis of the "highway operating and maintenance price index."[8,9] These estimated 1977 equivalent costs are shown in brackets.

The efficiency of paving as a control method depends very directly upon the characteristics of the unpaved surface being considered for treatment. By simply comparing the range of emission factors for paved and unpaved roads developed by Chatten Cowherd *et al*. at Midwest Research Institute, we can begin to estimate the range of control efficiency:[2,10]

		paved emissions	
	industrial	residential	commercial
unpaved emissions	.0243 lb/veh-mi	.0108 lb/veh-mi	.0026 lb/veh-mi
South Carolina: 3.9 lb/veh-mi	99.38%	99.72%	99.93%
California: 13.2 lb/veh-mi	99.82%	99.92%	99.98%

In his M.S.E. thesis, J.W. Roberts presented emission factors for:[3]

- a gravel road	6.0-8.1	lbs/veh-mi
- a paved road without curbs	0.83	lbs/veh-mi
- a paved road with curbs-flushed weekly and swept bi-weekly	0.14	lbs/veh-mi

These data indicate that simple paving of the main road surface might yield 86 percent or more reduction of emissions, and that the addition of curbs in combination with periodic cleaning could bring the efficiency above 98%.

Watering

High rates of infiltration and evaporation combine to limit the general effectiveness of watering as a long-term means of dust supression. Nonetheless, it may be an appropriate control method for short-term supression of nuisance dust, such as during highway construction. Support for these beliefs is

TABLE 5.1. COST ESTIMATES FOR PAVING UNPAVED ROADS

Surface Type	Initial Cost ($/mile)	Life (yrs)	Change in Operating and Maintenance Costs ($/mile/yr)	Year	Source
1. 3" asphalt	26,400 [40,890]*	20	-2665[-3627]gravel	1973	Roberts[3]
2. low-type bituminous	-	5-12	-124[-267]gravel +219[+471]macadam	1965	Winfrey[4]
3. high-type bituminous	-	12-20	+195[+419]gravel +538[+1158]macadam	1965	Winfrey[4]
4. double bituminous	-	-	-1365 gravel	1977	Mississippi[5]
5. asphalt bituminous	-	-	-1020 gravel	1977	Mississippi[5]
6. 2" hot bituminous	19,000	3	-	1978	North Dakota[6]
7. "hot mix"	15,134[15,470]+6278[6417] per mi paved	-	-	1975	Vermont[7]

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[*] Figures in brackets are the corresponding dollar value in mid-1977 dollars.

found in both the open literature and the correspondence we received from the state highway departments:

> "...watering is not a feasible method of effective dust control on public roads because of the high frequency of treatment required. However it may be used advantageously on unpaved roads under special circumstances..." - Jutze and Axetell[11]

> "Water, as a means of controlling dust is too costly, time consuming, and ineffective to use when dealing with the many miles of non-hard surfaced roads we have. This is due to the quick evaporation of water, therefore necessitating many applications..." - State of Virginia[12]

To provide some quantitative basis for comparison of watering with other control methods, we cite the 1978 estimate of the State of North Dakota, "The average cost of water is $200/mile/day and, rating effectiveness, on a scale of 1-10 rates about 4."[6] Using this daily cost, and assuming that is used as a permanent control watering would be required on each dry day of the year, we find annual costs ranging from $41,400/mile in West Virginia to $62,800/mile in Arizona. Regional variations in water prices, which are not considered here, would be expected to increase the geographic variation in these annual costs.

Oiling

Oil may either be sprayed onto the road surface, or it can be mixed into the top few inches of surface material. Recycled oils, standard commercial oils, or specially formulated dust control oils, which typically are petroleum resins cut back with light hydrocarbon solvents, may all be used for dust control. Although oiling may intuitively seem an attractive intermediate between watering and paving, practice does not seem to support intuition:[11]

> "Application of a surface chemical treatment for dust suppression is a relatively inexpensive control method. However, in tests on public roads conducted by several different highway departments, no commercial material has been found which retains its effectiveness over a reasonable period of time (e.g., two months) under traffic conditions.... An alternative intermediate in cost and effectiveness between paving and surface treatment is working the stabilization chemicals into the roadbed to a depth of two to six inches. This construction technique has been used extensively in the San Joaquin Valley, where locally available petroleum by-products provide a cheap material for oiled earth roads... the results so far are not encouraging. The construction cost approaches that of a single bituminous chip seal surface, and the resulting road has a shorter lifespan with comparable maintenance..."

From our correspondence with state highway departments, it appears that oiling is not even particularly attractive for short-term control of dust:

> "On construction projects where temporary gravel roads are being maintained, watering seems to be the most cost-effective. Normally a contractor is given the option to either water or oil the road and he usually elects the watering option." - State of Michigan[13]

> "Very little dust oil has been used in our State...we require watering during construction..." - State of South Dakota[14]

Estimates of the cost and effectiveness of various methods of oiling for dust control are presented in Table 5.2.

The costs in brackets in Table 5.2 were adjusted to mid-1977 price levels using the "refined petroleum products index" to adjust materials costs, and the "general index of hourly and weekly earnings" to adjust applications costs.[17] Estimates of the required frequency of application necessary to maintain desirable surface properties and continuous control of dust are sparse, and highly varied. Whereas Roberts's estimate[3] of the average life of an oiled surface is four to six years, Sultan states that oil controls dust effectively for at most 25 days. An estimate of the difference in annual maintenance costs for gravel and oiled road surfaces is provided by Roberts[3]: gravel, $2910/mile; oiled, $1106/mile.

The control efficiency of oiling has been reported to be between 50 and 90 percent, as indicated in Table 5.2 presented below. Although we have not seen data reported in this form, it would seem clear that for any material and method of application the average efficiency of control is a function of the frequency of application.

Calcium Chloride

Calcium chloride has a deliquescent effect. At any relative humidity above 29 percent it will absorb moisture into the road surface from the atmosphere. In addition to the direct reduction of emissions due to this increased soil moisture, soil stability is increased as a result of compaction of clays. In arid and semi-arid regions it has found widespread application,as it is relatively effective and inexpensive. In regions which undergo frequent wetting and drying, it is impractical since calcium chloride is readily leached from the treated road surface.

The information which we obtained in correspondence from the state highway departments permits estimation of the cost and effectiveness of this control method:

> "...Calcium chloride is used in special cases and works best when the humidity is high. It costs $400/mile/week [1978] and rates 6 [on a scale of 10]. Calcium chloride is considered one of the best and most economical methods of dust control...." - State of North Dakota[6]

> "Presently the bulk of our dust control is done with calcium chloride... A calcium chloride treatment of one pound per square yard costs approximately 5¢...." - State of Virginia[12]

TABLE 5.2 COST ESTIMATES FOR OILING UNPAVED ROADS

Material	Method of application	Control efficiency	Cost ($/mile/application)	Year	Source
1. PS 300 oil	not specified(n/s)	n/s	2000[3202]	1973	Roberts[3]
2. Standard® Dust Control Oil	0.5 gal./sq. yd. - sprayed	(98%)	1100-3153[2650-7597]	1974	Sultan[15]
			+1492[1930]cost of application	1973	Roberts[3]
3. oil	not specified	n/s	5950	1978	
4. emulsified asphalt	not specified	(80%)	2000	1978	
5. Standard® Dust Control Roil	0.5 gal./sq. yd. - mixed 3 inches followed by 0.1 gal./sq. yd. spray	(88-91%)	1320-3784[3181-9117]	1974	Sultan[15]
			> +1472[>1930] application	1973	Roberts[3]
6. not specified	a. applied to prepared surface	(50%)	2000-3000[3322-4164]	1974	Jutze and Axetell[11]
	b. applied to unprepared surface	(50%)	1000-2000[1661-3322]	1974	"
	c. worked into the roadbed	(50%)	5000-12000[8305-19932]	1974	"

If these treatments were repeated weekly, the annual costs of application per mile treated would be $20,800 in North Dakota and $38,116 in Virginia.

A commercially available material, known as Soil-Lok, combines the properties of calcium chloride with those of sodium silicate. Experiments in arid regions demonstrated that sodium silicate is a very good dust-proofing agent. Sodium silicate is a good inorganic cementing material capable of bonding or hardening the soil. In combination, the two chemicals react within the sand pores to form an impervious gel which hardens, binding the sand particles into a solid mass. Although Sultan reported that Soil-Lok showed no damage after six months and that it affords good protection against wind erosion, he did not provide any information on costs or resistance to traffic and rain.[15]

Speed Control

As emission factors varyat least proportionally with vehicle speed, speed control is often suggested as a means of reducing dust emissions from unpaved roads. Although some have naively suggested that the only costs associated with speed control are the costs of administration and enforcement, we believe that social costs are imposed in the form of increased travel times.

The increased travel times are easily calculated. Using 40 mph as a reference, we can see that 0.5 minutes per mile will be added to travel times by a reduction to 30 mph, and 3.0 minutes per mile by a reduction to 20 mph. In order to estimate the social costs associated with these increases, we must consider traffic densities and the economic value of this "lost time."

Winfrey[4] in 1969 recommended valuing generalized passenger car travel between $1.00 [$1.68] and $4.00 [$6.67] per car hour. The Interstate Commerce Commission (1965) estimated that the value of time losses for commerical vehicles varied from $3.65 [7.66] to $8.29 [17.39] per hour.[4] These values have been adjusted to mid-1977 price levels using the "index of general hourly and weekly earnings."[17]

The control efficiency which we attribute to various degrees of speed reduction follows directly from the functional form of the relationship between average vehicle speed and emissions. On the basis of proportional relationships developed by Cowherd et al. we would expect a 25 percent reduction in emissions with a decrease from 40 to 30 mph, and a 50 percent reduction if average speeds were reduced from 40 to 20 mph.[2] Other researchers have suggested non-linear relationships:

1. Jutze, Axetell, and Parker of PEDCo Environmental Specialists developed emission factors for six AQCR's in New Mexico, Nevada, Arizona, California, and Texas.[11] Their equation of best fit for vehicle-generated dust was:

$$E = 0.27 \times (1.068)^{S}$$

where: E = emission factor (lb/veh-mi)
S = average vehicle speed (mph)

To this must be added a term accounting for wind erosion of the unpaved surface. This second term was derived from the empirical wind erosion equation of Woodruff and Siddoway[18]. Using a wind erosion rate of 3 tons/acre/year, or 9 tons/mile/year, we have combined wind and vehicle generated emissions of:

$$E = [0.27 \times (1.068)^S] + \frac{49.3}{ADT}$$

where: ADT = average daily traffic (veh/day)
and all other terms are defined above.

2. Roberts, Watters, Mangold, and Russano in Seattle, Washington developed the following emission factors for gravel roads:[2]

speed (mph)	observed emission factor (lb/veh -mi)	estimated emission factor (lb/veh -mi)
10	3.5	3.3
20	7.0	8.2
30	22.0	20.7
40	-	52.3

We have fit these data to the equation:

$$E = 1.29 \times (1.097)^S$$

Exploring these relationships, we see that Robert's data would suggest a 60 percent reduction in emissions accompanying a speed reduction from 40 to 30 mph, and a 84% emissions reduction with a reduction to 20 mph. The PEDCo data demonstrate the dependency of emissions reduction efficiency on traffic density:[11]

Speed Reduction	Average Daily Traffic		
	50	500	∞
40→30 mph	38%	47%	48%
40→20 mph	58%	71%	73%

Intuitively it might seem that speed reductions should be credited with reduction of the frequency and severity of accidents. However, we have not been able to find reliable data on accident frequency or severity as a function of average vehicle speed, applicable to unpaved roads.

COST-EFFECTIVENESS RATIO

From this basic information on the components of cost and anticipated efficiency of control we can compute a single number which characterizes the relative cost-efficiencies of the various control methods. Let us arbitrarily select a mile of unpaved road as the unit of interest.

First, we must adjust all costs to the same price levels. We have chosen to adjust to the levels which prevailed in mid-1977. Then we must combine the costs of capital investments with the recurring costs associated with maintenance. To combine costs which occur at different points in time, one can compute annualized cost. The total annualized cost is the average yearly cost of items which involve repeated yearly expenditures, such as maintenance, plus a yearly pro-rating of costs which do not, in fact, occur yearly, such as initial capital investment. To calculate the total annualized cost we add the average annual cost of operation and maintenance, AC, to the product of the capital recovery factor, CRF, and the initial capital investment, K. (The capital recovery factor is the percentage of the initial investment which one would pay yearly on a loan or mortgage, at an interest rate, i, for the life of the loan, n years.) The relevant equations are:

$$TAC = AC + (CRF)K$$

$$CRF = \frac{i(1 + i)^n}{(1 + i)^n - 1}$$

In Table 5.3 we summarize the range of estimates of the total annual costs of application of each of the feasible control methods to one mile of unpaved road. The figures in the table are based upon a discount rate, i, of 10 percent per year. Without further computation, it is clear that any method which has both higher annualized costs and lower control efficiency than some other method, can be culled. Similarly if one method has both lower annualized costs and higher control efficiencies than the others, it clearly dominates. Generally, however, it will be helpful to calculate a single index of relative cost-efficiency. In Table 5.4 we have divided the total annualized costs by the control efficiency of each method to derive such a measure. The wide ranges in these cost estimates reflect two influences: regional variation in the costs, lifetimes and efficiencies of control; and imprecision and uncertainty in the estimates of these parameters. In the face of uncertainty, an initial selection of the dominant control technology may be made by examining the mid-ranges of the cost estimates.

Although speed control from 40 mph to 30 mph appears to be economical for roads with low traffic density (≤ 80 vehicles/day), for permanent or continuous reduction of emissions from roads with more typical traffic densities, paving appears to dominate, with a standardized total annual unit cost of $88.98/yr-mile-percent control, or $7653/yr-mile at 86 percent control efficiency. This analysis suggests that regardless of location or existing road surface type, by paving we can reduce mass emissions more for each dollar spent on control than through the application of any other control technique.

Now, if we are interested in maximizing the nation-wide reduction of dust emissions for various levels of national control expenditure, we must account for regional variations in emissions factors and traffic densities. For example, it is clear that paving a road in California (average statewide emission factor = 13.2 lbs/veh-mi) will reduce national dust emissions more than paving a road with similar traffic density in South Carolina (average

TABLE 5.3. ESTIMATED COSTS AND DUST EMISSION REDUCTIONS OF VARIOUS TREATMENTS FOR UNPAVED ROADS.

Control Method	Total Annualized Cost Estimates ($/yr /mile @ i=10%)		Range of Efficiencies (% reduction)
	low	high	
paving	-1,810	+16,861	86-99.98
oiling	-1,423	+291,413	50-98
watering	41,400	62,800	40
calcium chloride	20,800	38,116	60
speed control: 40 to 30 mph	5.08 x ADT	52.68 x ADT	25-60
speed control: 40 to 20 mph	30.60 x ADT	317.35 x ADT	50-84

TABLE 5.4 COST-EFFECTIVENESS RATIOS FOR UNPAVED ROAD TREATMENTS

Control Method	Estimated Cost-Efficiency Ratio [TAC ($)/mi /% reduction]		
	low	high	midrange
paving	-$18.10	$196.06	$ 89.
oiling	- 14.52	5826.28	$2906.
watering	1035.00	1570.00	$1302.
calcium chloride	346.67	635.27	$ 491.
speed control: 40→30 mph	.0846 x ADT	2.1072 x ADT	1.096 x ADT
speed control: 40→20 mph	.3643 x ADT	6.347 x ADT	3.355 x ADT

statewide emission factor = 3.9 lbs/veh-mi). Similarly, within any region with similar emission factors, it will be more effective to pave zones of high traffic density, e.g., ADT = 5000, than zones experiencing less traffic, e.g., ADT = 10.

We take a first look at this problem by disaggregating to the state level. We make the further distinction between urban and rural areas. In the work that follows, the average annual emissions per mile of unpaved road were calculated for the urban and rural roads in each state, by multiplying the average statewide emission factor by the average annual urban and rural traffic densities. After ordering these values from the highest uncontrolled emissions per mile per year to the lowest, we calculate the decrease in national mass emissions available for any level of control expenditure simply by applying the mid-range estimates of paving cost and efficiency to these data. The results are given in tabular form in Table 5.5 and plotted below in Figure 5.1. The information contained in Table 5.5 implies that in general unpaved roads in urban areas should be paved before those in rural areas, and that among rural areas priority should be given to Arizona over Colorado, and to Vermont over South Carolina, and so forth. We do not mean to suggest that there may not be specific regions of Arizona, but on the average it is more efficient to pave roads in Arizona than in Colorado.

From the tables and graph, we can see that these costs of control are in the range of \$0.01 to \$0.02 per pound avoided for most urban roads and \$0.03 to \$0.12 per pound avoided for most rural roads. For comparison, estimates of the costs of control of point sources of particles vary from approximately \$0.01 to \$0.18 per pound.[19] If we were confident that reduction of a pound of road dust emissions could be expected to have the same impact as reduction of one pound of point source emissions, we would point out that before more stringent controls on industrial sources are considered, some thought should be given to open source control.

The linear regression analysis described in Appendix G shows that state-to-state variations in annual median TSP levels are much less strongly dependent on open source emissions rates than on point source emission rates, on a per ton basis, thus somewhat offsetting the apparent control cost advantage of reducing unpaved road emissions.

TABLE 5.5. ESTIMATED COSTS OF CONTROL FOR UNPAVED ROAD DUST FOR URBAN AND RURAL ROADS, BY STATES

Estimated Cost of Control $/lb	Rural Unpaved Roads	Municipal Unpaved Roads	Amount of Unpaved Road Dust Controllable 10^9 lb/yr	Total Cost of Control $\$10^9$/yr
0.000-0.005	DE.	CA, MD, NJ.	13.0	0.047
0.005-0.010	RI.	AK, AZ, DE, MI, NV, PA, CO, FL, IL, IN, KY, MA, NM, OH, OR, RI, TN, TX, UT, VA, WA, WV.	35.8	0.289
0.010-0.015	AZ, CA, NJ.	CT, GA, MO, MT, NE, OK, WI, KS, LA, MN, NY, NC, WY.	72.6	0.904
0.015-0.020	AK, CT, HI, NH, PA.	AL, IA, ME, MS, AK, ID, NH, ND, SD, VT.	23.3	0.409
0.020-0.025	AR, LA, MD, NM, NY, TX, WV.	SC.	89.0	2.00
0.025-0.030	CO, FL, IN, IA, MA, MI, NC, OK, OR, UT, VT, VA.		122.	3.36
0.030-0.035	GA, IL, KS, KY, ME, MN, MO, NE, OH, TN, WA.		122.	3.97
0.035-0.040	AL, MS, MT, NV, WY.		36.5	1.37
0.040-0.045	ID, SD.		17.2	0.731
0.045-0.050	ND, WI.		19.1	0.907
0.050-0.055			0.0	0.0
0.055-0.060			0.0	0.0
0.060-0.065	SC.		2.06	0.129

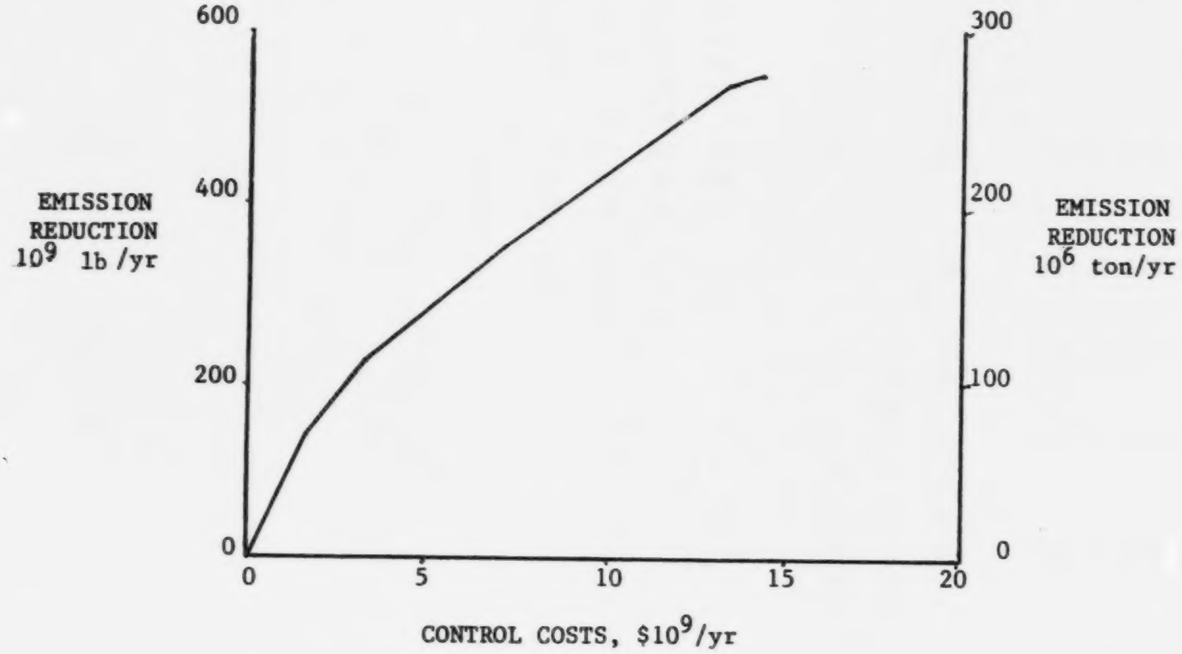

Figure 5.1. Unpaved road dust emission reduction versus control cost.

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SECTION 6

CONCLUSIONS

The most important parts of this report are probably those dealing with results (emission rates, cost-effectiveness), not the conclusions which we draw from them. However, there are aspects of the work for which conclusions are appropriate.

GOAL DEFINITION

Theoretically, an equitable cost-benefit analysis (or net utility analysis, also weighted for equity) would be most appropriate for translating our goals into criteria by which policies could be evaluated. Having assessed the difficulties involved in such analyses, we believe that at present it is preferable to use cost-effectiveness as a means of comparing policies, by comparing the costs for reaching approximately the same set of conditions (such as TSP levels).

PROBLEM IDENTIFICATION

Based on emission estimates and upon analysis by others of particulate material (for total suspended particulates) captured in samplers, unpaved road emissions are greater contributors to TSP levels than are particulate emissions from point sources. Wind erosion of cropland and emission of dust due to construction activities are estimated to be roughly the same as particulate emission rates from point sources. Emissions from paved roads are smaller than from point sources, but not by an order of magnitude. Although some of these sources may not have their particulates transported as far as do point sources and although the particulates may not be of the same toxicity, open sources should no longer receive substantially less attention than do point sources.

Emission Factors

There have been about a half-dozen studies of emission factors for unpaved roads, and additional work is not likely to change the emission factor estimate greatly. The factors for wind erosion of cropland have also been studied intensively, by agricultural researchers, but the current estimate that suspended particulates are 2.5% of the wind erosion is based on very limited data. The construction emission estimate of 1 ton per acre per month is also based on very limited data. There is disagreement (about a factor of five) about the proper factor for tailings piles, though we have chosen the lower of the two estimates after comparing their rationales. Further assessment of the amount of suspendable dust on paved roads and how it is affected by various factors is of interest to us to pursue and seems worthwhile.

Source Extents

Data on average daily traffic (ADT) on urban and rural paved and unpaved roads have probably been collected, but they need to be located and obtained in order to sharpen the emission rate estimates made here. (There is also a wide range in the lifetimes ascribed to the paving on roads.) The current method of estimating construction activity, based on construction expenditures and the locations of construction workers, needs improvement. Up-to-date information on the acreages exposed to wind erosion because of mining operations is also needed.

Inter-relationships

States with dry and windy climates will, as expected, tend to have several open source emission problems: unpaved roads, wind erosion from cropland and construction sites and mineral extraction and beneficiation operations, agricultural tilling. The biggest source of emissions, unpaved roads, is highly correlated with non-road emissions, also indicating that states with at least one open source problem have many. The open source problem is not peculiar to just a few states, however; in fact, total emissions are quite strongly correlated with state population and, to a lesser degree, area.

PRIORITIES

The emission rate for unpaved roads is an order of magnitude larger than other emission rates. Construction emissions are much smaller, yet still very large, and they are strongly correlated with state population, thus are likely to be important in exposure of populations. We have shown that in some locations paving unpaved roads can be quite cost-effective as a means of pollution control; we suspect the same is true of control of construction emissions. (Agricultural emissions, because of the vast areas, seem much more difficult to control cost-effectively.) Control of unpaved road emissions and control of emissions from construction activities warrant high priority in the effort to reduce TSP levels nationwide. We do not know whether any of the especially toxic particulates listed in Appendix D deserve higher priority, and that question should receive consideration.

APPENDIX A

SETTING PRIORITIES FOR THE CONTROL OF PARTICULATE EMISSIONS FROM OPEN SOURCES

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Presented at the U.S.E.P.A. Symposium of the
Transfer and Utilization of
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Denver, Colorado, July 1978

ABSTRACT

Open sources of particulate emissions include agriculture, roads, forest fires, construction sites, and mineral extraction, etc. Control technology research, development, and application need the setting of priorities to be optimally effective. One criterion for optimization is cost-effectiveness, which can be determined by maximizing the weighted sum of emission reductions, within budgetary and technological constraints. Annual open source emission rates for the United States are reviewed and revised as a guide to the most significant sources. Control cost information is developed and used to formulate a cost-effective strategy for controlling the greatest source, unpaved roads.

INTRODUCTION

The results of air sampling indicate that the National Ambient Air Quality Standards for total suspended particulates (TSP) are not being met for a majority of the Air Quality Control Regions. In 1976 the national average TSP concentration increased from 1975, and increase attributed to higher-than-average contributions from nonindustrial sources of particulate emissions[1]. We are conducting a study for EPA on setting priorities for the control of dust from open sources, sources too large in extent to be controlled by enclosures and ducting. That program has as its goals the identification of the major open sources of particulate emissions and the consideration of alternative analyses for setting priorities for their control, such as ranking on the basis of cost of control or the hazard to the population, etc. In this paper, major open sources of particulate emissions are analyzed to attempt to rank them in order of emission rate (tons/year) for the U.S. as a whole and for each state; cost and effectiveness of control are analyzed for the suppression of road dust from unpaved roads, one of the largest sources (in tons/year) of suspended dust; and it is shown how the results of many such cost-effectiveness analyses could be combined to determine an optimally cost-effective strategy.

EMISSION FACTORS

The emission factors used to prepare our emission rate estimates are listed in Table 1. Each factor is the estimate of the amount per unit of source extent of emissions of suspendable dust, particles smaller than 30 μm with assumed densities of 2.5 g/cm^3, thus particles with aerodynamic diameters less than 48 μm. These emission factors are discussed very briefly next.

Agricultural Tilling

The amount of dust produced per acre during agricultural tilling depends upon many factors, including soil type, soil moisture, vehicle speed, etc. Emission factor values for the counties in the U.S. were provided by the Environmental Protection Agency[2] based upon the work of Cowherd, Southerland and Mann.[3] We selected the median county value to characterize each state, and these values are listed in the second column of Table 1.

Agricultural Erosion

The dust produced by wind erosion of agricultural soil depends upon soil type and moisture, wind velocity, vegetative cover, and field and surface geometry. The emission factor used in the third column of Table 1 was determined by using the formula:[4]

$$E_s = 0.025\ I\ K\ C\ L'\ V' \qquad (1)$$

where

E_s = suspended particulate erosion from fields, tons/acre-year;
I = soil erodibility, tons/acre-year;
K = surface roughness factor, dimensionless;
C = climatic factor, dimensionless;
L' = unsheltered field width factor, dimensionless;
V' = vegetative cover factor, dimensionless.

This equation was derived from a formula for wind erosion by using field measurements to estimate that 2.5% of the soil which erodes becomes airborne as suspendable particulate material.[4] I, the erodibility, depends upon soil type; it is the erosion for a flat, very large but bare field in a dry and windy climate.[5] K, C, L', and V' are correction factors. C can be determined from:[5]

$$C = 0.345\,\bar{v}_{30}/(PE)^2 \qquad (2)$$

where $\bar{v}_{30}$ = mean wind velocity at 30 feet above ground, mi/hr;
PE = Thornwaite's precipitation-evaporation index.

To determine $\bar{v}_{30}$, we started initially with 237 values for $\bar{v}_{15}$ for the fifty states.[6] These 237 ranged from 4 to 80 miles per hour, but five of them seemed clearly erroneous or atypical; after dropping these five values, we had a new range, 4-15 mph, which illustrates the degree to which these 5 values (35, 56, 65, 73, 80 mph) were outliers. This left no value for Maryland, so the mean of the values for the bordering states was used (8.5 mph). The mean wind velocity for each state was calculated and then corrected for a height of 30 feet by using the formula:[7]

$$v_2/v_1 = (z_2/z_1)^a \qquad (3)$$

with a = 0.5 (appropriate for z = 2 to 10 m under neutral conditions); thus, $(30/15)^{.5} = 1.414$ was used as correction to $\bar{v}_{15}$ to obtain $\bar{v}_{30}$. To check our values for the C factor against those widely used, we determined approximate state-by-state area-averaged values of C from a map of C values covering 37 states.[5] The C factors we calculated ranged from .012 to 1.38; the coefficient of determination for the 37 state area-averaged values versus the corresponding 37 of 50 calculated from equation 2 was $r^2 = 0.86$; the slope was 1.24; one can conclude that the two methods agree rather well, the area-averaged values being generally about one-fourth higher.

Cowherd et al.[4] presented tables which give typical values of K, L, and V for various crops. From the data giving crops and acreage by state,[10] we derived area-weighted averages of K, L, and V for use in determining the surface roughness and the L and V factors to be used in the wind erosion equation.[11]

Although one can estimate the factor for unsheltered field length, L', the correction factor is difficult to compute and is generally quite close to one (see example in the paper by Woodruff and Siddoway[11]). The correction factor was not incorporated into our estimates. We did, however, correct for vegetation, using the vegetative cover factor[11] appropriate to the soil erodibility and vegetation characterizing each state, because vegetation factors can be a factor of two or even greater.

Predominant soil type used to determine I, the erodibility index, was determined from a soil map in The National Atlas of the United States.[12] For most states, the analysis was straightforward: the soil type covering 50% or more of the area was used for the entire state. For several states there was not one soil type covering more than half the area, so the areas of two or more soil types were estimated and used to form a weighted average erodibility index. In the following states, the soil that predominated in the farming areas was used instead: California, Florida, Hawaii, Nevada, New Mexico, New York, Washington State, Wyoming. (The erodibility indices used for each state will be made available upon request.)

Construction

Dust emissions at construction sites are generated by such operations as land clearing, blasting, ground excavation, cut and fill operations, and construction. Dust activity also varies according to level of activity and weather conditions.[9] The median values of construction emission factors were again selected by state from county-by-county data supplied by the Environmental Protection Agency.[4] These factors are based upon the approximate emission factor for construction of 1 ton/acre-month[3] adjusted by the following assumed durations of construction:[3] six months for residential building, eleven months for non-residential building, and eighteen months for non-building construction activities. The resulting emission factors are in column four of Table 1.

Forest Fires: Wildfires

Our review of the literature indicated that the best estimates of emissions from forest fires, both wild and prescribed, are those of Ward et al.[14] The emission factors in column five of Table 1 are obtained by using their estimate that 150 lb/ton of wood burned is emitted as suspendable particulates, along with the typical values presented by Yamate et al. for the tons of wood per acre for forested regions in the respective states, to give tons of particulate emitted per acre burned, by state.[8,9]

Forest Fires: Prescribed Burning

Using 50 lb/ton as the emission from prescribed burning[14] and tons/acre data from Yamate et al. the values in the sixth column of Table 1 were obtained.[8,9]

Mineral Industries: Bituminous Coal

Surface mining of coal produces particulate emissions as the "overburden" material is removed to get at the coal. In the East and Central U.S. the ratio of overburden thickness to coal thickness is 10:1 to 20:1 and in the West the ratio is closer to 1:3.[15] Oschner and Blackwood[16] cited emission factor values of 0.17 lb/ton of overburden removed, based on research done by Monsanto Research Corporation, and cited other estimates from 0.048 to 0.1 lb/ton of overburden. A 10:1 overburden-to-coal ratio and 0.17 lb/ton of overburden gives an emission factor of 1.7 lb/ton of coal from Eastern and Central surface mining operations. In these same regions, the amount of coal per acre is about 2600 tons[15], and the time during which the land is disturbed (from initial removal to return and replanting) is several months[15] (Using the emission factor estimate for construction of 1.2 tons/acre-month of activity gives a value of 3.7 lb/ton of coal produced, not very different from the 1.7 lb/ton factor.). To estimate the emissions from bituminous coal surface mining, we have used 1.7 lb/ton of coal for the East and Central states and about 1/30 of this value (0.06 lb/ton) for Western coal production. These values are very approximate, however, as they do not take into account important details such as climatic factor and soil type. Column seven in Table 1 gives emission factors by state for bituminous coal.

Mineral Industries: Other Surface Mining

Noting the values for coal given above, we used a rough estimate of 2 lb/ton (0.1%) of material which is surface mined, but this we believe correct, as an average for all such mining, only to within an order of magnitude. This estimate is indicated in column eight of Table 1.

Roads: Paved

Column nine in Table 1 indicates an emission factor of 0.013 lb/vehicle-mile as an emission factor for paved roads.[18] This factor depends on land use and indicates a mean value (residential, industrial, commercial).

Roads: Unpaved

Unpaved road emissions depend upon surface texture and material, surface moisture, vehicle speed and type. Cowherd et al.[3] developed an emission factor for roads which depends upon road surface, silt content, average vehicle speed, and the number of dry days per year; from county levels they determined, the median values for each state were selected for use as characteristic of the individual states;

these medians are shown in Table 1 under the last column.

SOURCE EXTENTS

The measures of source extent used to prepare our emission rate estimates are listed in Table 2 and discussed below.

Agricultural Tilling and Wind Erosion

The second column in Table 2 gives the number of acres of harvested cropland by state. This is the measure of source extent for wind erosion from such land; multiplied by three (for an average of three tillings per year), the numbers become the measure of source extent for agricultural tilling emissions.

Construction

Conversion factors developed by Midwest Research Institute were used by us to calculate total acreage of active construction, based upon construction expenditures for each Standard Industrial Code (SIC) classification for each state:[3,19]

SIC code	Description	Factor (acres/$\$10^6$)
1521	General contractors-single family houses	5
1522	General contractors-residential buildings other than single family	5
1531	Operative builders	5
1541	Industrial buildings and warehouses	5
1542	Non-residential buildings, N.E.C.	5
1611	Highway and street construction	25
1622	Bridge, tunnel and elevated highway construction	25
1623	Water, sewer and utility lines	5
1629	Heavy construction, N.E.C.	150

Column three in Table 2 gives the calculated acreage of active construction in each state.

Forest Fires: Wildfires and Prescribed Burning

Forest acreage, the source extent for forest fires, was obtained from work by Ward et al.[14] Acreage values were derived by them from averaging ten years of data, 1963-1972, from Wildfire Statistics,[20] published by the Forest Service, U.S. Dept. of Agriculture for those years. (Most, but not all, of forest acreage in the U.S. is included in these values.)

Mineral Industries: Bituminous Coal

Annual tonnage of coal produced, the measure of source extent, was obtained by compiling state coal production figures found in the most recent Minerals Yearbook (1974).[21] These production figures are found in column six of Table 2.

Mineral Industries: Other Surface Mining

State values for material handled at surface mines, available from the latest Minerals Yearbook,[21] provided us with our measure of source extent, total annual tonnage produced.

Roads: Paved and Unpaved

The miles of paved and unpaved roads by state were obtained from statistics issued by the Federal Highway Administration.[22] Information from the State of Mississippi indicated that sand, gravel, slag and dirt surfaced roads receive about ten percent of the per mile use of asphalt and concrete surfaces. Therefore, we apportioned the annual vehicle miles traveled according to the formulas:

$$aP + bU = V \tag{4}$$

$$b/a = 0.1 \tag{5}$$

where

P = paved mileage in state;
U = unpaved mileage in state;
V = total vehicle miles traveled in state yearly;
a = use factor for paved roads;
b = use factor for unpaved roads.

These two equations allowed the calculation of a and b and thus the calculation of the amount of miles traveled annually on unpaved roads, bU, and on paved roads, aP, shown in Table 2.

EMISSION RATES

Our estimates of emission rates for each of the sources was obtained by multiplying its emission factor with its source extent. The resulting emission rate is indicated for each source for each state in Table 3. The national total emission rates by source category are:

Source type	Particulate Emissions (10^6 tons/yr)
Agricultural tilling	3.3
Wind erosion of harvested cropland	23.3
Construction	27.4
Wildfires	3.4
Prescribed burning	0.4
Surface mining	3.2
Unpaved roads	325.6
Paved roads	8.4
Total	395.0

As a point of comparison, total point source emissions in the U.S. are on the order of 20 million tons/year.

ECONOMICS OF OPEN SOURCE CONTROL

Estimation of the magnitude of emissions is a very preliminary step in the evaluation of the significance and feasibility of control of open sources. Particles are thought to impair health, increase rates of weathering and corrosion of materials, contribute to the damage of vegetation, and decrease visibility. The decision to control fugitive dust, and the selection of a strategy of control, affect society in two ways: the amount, type, and location of damage done by particles is altered, and resources are diverted from other uses to control open sources of emissions.

Here is outlined a method which allows one to minimize the national costs (diversion of resources) associated with any level of emission reduction.* We leave to others an examination of the physical and economic benefits of these emission reductions.

Stated briefly, for each source class (i.e., agricultural tilling, unpaved roads, ...), one proceeds through a six step sequence, leading to the evaluation of cost-effectiveness:

1. determine the feasible control methods;
2. evaluate the components of control cost and efficiency;
3. calculate the total annual cost of control per unit of source extent;
4. standardize the total annual costs, dividing by control efficiency;
5. select the dominant control method;
6. calculate the cost efficiency of the dominant method in each state.

Finally, when this analysis is completed for each source class, one can rank the results, and prepare a tabulation of the maximum mass of dust emissions which can be prevented each year for any level of control expenditure.

In highly summarized fashion, we present below our preliminary cost-effectiveness analysis of the largest of the open sources of emissions, unpaved roads.

COST EFFECTIVENESS: EMISSIONS CONTROL FOR UNPAVED ROADS

Widely-used methods of dust control include paving, oiling, watering, and the application of calcium chloride. Speed reduction is often suggested as an emission control method, since emission factors increase at least proportionately with vehicle speed. Although many methods of chemical stabilization have been tested (and appear to be more effective than oiling), not enough economic data is available to permit evaluation of their cost efficiency.

Table 4 presents data on the standardized total annual costs of these methods of control. The wide ranges in these cost estimates reflect two influences: regional variation in the costs, lifetimes and efficiency of control; and imprecision and uncertainty in the estimates

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*Alternatively stated, we wish to maximize the reduction in emissions for any level of control expenditure. Note that our problem is analogous to traditional cost-effectiveness or capital budgeting problems.

Table 4. COST EFFICIENCY OF ALTERNATE METHODS OF DUST CONTROL: UNPAVED ROADS

	Annual cost* $/mi-gr-%		
	Low	High	Midrange
Asphalt Paving	-34	199	83
Speed Reduction-30	6	676	341
Calcium Chloride	353	788	571
Speed Reduction-20	12	1,353	683
Watering	1,061	1,847	1,454
Oiling	-22	40,532	20,255

*Cost in 1977 dollars per year per mile of road treated per emission reduction percentage. (Discount rate = 10%)

of these parameters. In the face of uncertainty, an initial selection of the dominant control technology may be made by examining the midranges of the cost estimates. Using this measure, paving appears to dominate, with a standardized total annual unit cost of $83/mile-year-% control, or $7055/mile-year at 85% control efficiency.

To complete the analysis, one must calculate the uncontrolled emission rate from a mile of unpaved road in each state. The cost effectiveness of the dominant control method in each state may then be determined.

$$\text{cost effectiveness} = \frac{\text{uncontrolled emissions (lbs/mile-yr)}}{\text{total annual unit control cost (\$/mile-yr-\%)} \times \text{control efficiency (\%)}} \quad (6)$$

Table 5 gives these data for urban and rural unpaved roads in each state. Clearly, control of municipal roads is more cost effective than control of rural roads. Note that these costs are in the range of $0.01 to $0.02 per pound avoided for municipal roads and $0.03 to $0.12 per pound avoided for rural roads. For comparison, estimates of the costs of control of point sources of particles vary from approximately $0.01 to $0.18 per pound.[23]

Table 5 indicates how much dust can be controlled in each $0.02 per pound price interval. Figure 1 demonstrates how these state-by-state estimates of cost efficiency can be combined for the 50 states to form a piecewise linear function relating annual control expenditure to emission abatement.

These results should not be used as the basis for policy recommendations without first answering several questions:

1. How wrong could these numbers be?
   - Are control costs correct?
   - Are control efficiencies and treatment lifetimes reasonable?
   - What about the relative traffic densities on paved and unpaved roads?

2. Is paving clearly the dominant control technology?
   - Can it be applied everywhere?
   - If so, at the calculated unit cost?

3. Finally, and perhaps most important: Is a pound of emissions from an unpaved road as significant as a pound of emissions from coal combustion, the steel industry, etc.?

CONCLUSIONS AND RECOMMENDATIONS

In summary, open sources are significant emissions sources, approximately 395 million tons per year in the U.S. It appears that roads, agriculture, and construction are the major sources nationally.

Much remains to be done. Emission rate estimates for open sources require more research concerning road dust entrainment and the amount of dust typically on roads of different types and uses, as well as research into the emission factors for construction, surface mining, and for wind erosion of range and desert land. Control methods, their efficiencies, and their costs all warrant further investigation, although much progress has been made in the study of vegetative and chemical stabilization of wastes.[13,17]

For particles not significantly more toxic than soil, cost effectiveness of mass emissions reduction may be a reasonable method of initial control prioritization. The significant regional variations in cost-effectiveness of control should be considered in formulation of control strategies.

It seems that dust from unpaved roads can be controlled at costs similar to those for the control of industrial point sources. However, once dominant, and near dominant, control techniques have been identified for each source class, careful engineering and economic studies may be required to resolve the uncertainties which now shroud estimates of control costs, lifetimes, and efficiencies.

Finally, toxicity, respirability, and transport of dust from open sources must be adequately characterized before sensible policy decisions can be made.

ACKNOWLEDGMENTS

We extend our thanks to Dr. Dennis C. Drehmel of the U.S. EPA for his economic and moral support of this work, the countless Federal and state officials who have graciously responded to our requests for data, Richard Antonelli for his unending assistance in compiling and analyzing data, and Laurie Cassel for her flawless preparation of the manuscript.

ERRATA

In preparing the main report to which this is Appendix A, we discovered that the value of acres of harvested cropland for Oklahoma should be 8.99 million rather than 3.99 million, which would raise the wind erosion and agricultural emission estimates by the factor 8.99/3.99 = 2.25. We noted anomalies in the wind erosion emission rates for several states; we recalculated wind erosion values for all the states, using the method of Woodruff and Siddoway, and found numerous errors in the original numbers, with no consistent explanation. These have been corrected in the main report. Similar checks for errors in the other emission estimates did not disclose any. The authors apologize to any users of the incorrect values published in the proceedings of the symposium.

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Table 1. OPEN SOURCE EMISSION FACTORS BY STATE

State	Agriculture		Construction	Forest Fires		Mineral Extraction		Roads	
	Tilling	Wind Erosion		Wild	Prescribed	Coal	Other	Paved	Unpaved
	lb/acre	ton/acre	ton/acre	lb/acre		lb/ton		lb/veh-mi	
AL	3.79	.006	16.50	1350	150	1.7	2	0.013	7.39
AK	11.90		17.70	1650	Negl.	1.7	2	0.013	9.69
AZ	214.00	.721	16.10	1500	400	.06	↓	↓	12.11
AR	4.40	.036	16.20	1350	150	1.7	↓	↓	7.94
CA	30.30	.537	17.50	2700	3500		↓	↓	13.20
CO	53.00	.045	15.70	4500	400	.06	↓	↓	8.17
CT	5.63	.026	16.70	1050	0		↓	↓	6.39
DE	2.66	.030	14.30	300	100		↓	↓	5.99
FL	4.34	.044	15.70	900	200		↓	↓	5.33
GA	4.06	.028	17.20	1350	150		↓	↓	5.58
HI	30.20		14.80				↓	↓	5.97
ID	39.20	.022	17.90	9000	3250		↓	↓	8.17
IL	14.00	.124	17.10	1650		1.7	↓	↓	7.10
IN	9.33	.090	17.20	1650	0	1.7	↓	↓	6.96
IA	12.30	.015	16.80	900	0	1.7	↓	↓	7.39
KS	24.10	.045	17.10	450	0	1.7	↓	↓	8.95
KY	8.14	.034	17.00	1650	Negl.	1.7	↓	↓	6.68
LA	7.93	.034	17.40	1350	150		↓	↓	7.39
ME	5.47	.021	16.60	1350	0		↓	↓	7.25
MD	2.90	.037	13.90	1050	0	1.7	↓	↓	5.99
MA	4.84	.020	13.50	1650	0		↓	↓	6.39
MI	6.72	.100	16.70	1650	150		↓	↓	6.68
MN	11.10	.016	16.80	1650	No data		↓	↓	7.24
MS	5.38	.016	16.20	1350	150		↓	↓	6.85
MO	10.50	.107	16.50	750	No data	1.7	↓	↓	7.39
MT	47.60	.014	15.80	7350	2250	.06	↓	↓	9.59
NE	37.50	.049	16.90	450	0		↓	↓	8.70
NV	245.0	2.226	13.90	1200	No data		↓	↓	10.43
NH	6.39	.005	15.90	1200	0		↓	↓	9.59
NJ	6.03	.052	17.00	1500	150		↓	↓	8.79
NM	103.0	.053	16.00	1500	400	.06	↓	↓	10.26
NY	9.69	.512	16.80	1650	0		↓	↓	6.71
NC	3.08	.037	16.80	1350	150		↓	↓	6.52
ND	30.40	.020	16.10	450	100		↓	↓	9.99
OH	9.14	.081	17.00	1650	0	1.7	↓	↓	6.47
OK	19.40	.023	17.20	450	No data	1.7	↓	↓	8.95
OR	24.50	.026	16.90	9000	1650		↓	↓	9.70
PA	11.10	.020	17.40	1650	0	1.7	↓	↓	8.59
RI	8.03	.041	11.20	1050	0		↓	↓	7.99
SC	3.80	.036	14.90	1350	150		↓	↓	3.87
SD	28.30	.030	16.50	600	No data		↓	↓	9.11
TN	5.83	.019	16.20	1350	No data	1.7	↓	↓	6.44
TX	40.60	.064	17.60	900	150		↓	↓	10.30
UT	144.0	.618	17.00	1200	Negl.	.06	↓	↓	10.21
VT	6.63	.057	14.60	1200	0		↓	↓	6.87
VA	4.32	.019	16.40	750	250	1.7	↓	↓	5.99
WA	5.90	.009	17.20	9150	1700	.06	↓	↓	8.77
WV	11.10	.010	17.40	1800	0	1.7	↓	↓	8.95
WI	10.50	.115	15.70	1650	No data		↓	↓	7.39
WY	67.00	.048	16.80	900	0	.06			8.29

Table 2. OPEN SOURCE EXTENTS BY STATE

State	Agriculture	Construction	Forest Fires		Mineral Extraction		Roads	
	Tilling Wind Erosion		Wild	Prescribed	Coal	Other	Paved	Unpaved
	10^6 Acres of Harvested Cropland	Acres	Acres		10^3 tons/yr		10^9 veh-mi	
AL	2.794	16,559	151,150	208,505	19,824	39,300	22.90	1.02
AK	.017	3,355	783,994	0	700	127,000	1.68	.41
AZ	1.097	8,615	38,051	25,956	6,448	187,000	14.08	1.61
AR	6.639	8,676	139,970	54,736	455	38,000	11.16	2.35
CA	8.307	277,394	162,070	12,104		171,000	123.42	4.17
CO	5.957	7,459	11,106	2,594	6,896	33,800	13.69	2.47
CT	.159	19,914	1,982	0		15,100	17.91	.10
DE	.452	721	307	950		2,410	3.45	.02
FL	2.304	48,787	703,490	718,877		235,000	59.39	2.63
GA	4.161	26,438	61,123	724,616		54,600	32.57	2.51
HI	.151	4,203				9,010	3.89	.03
ID	4.531	1,363	120,892	27,906		17,800	4.65	1.01
IL	21.518	79,921	13,881	0	58,215	104,000	56.97	2.24
IN	11.234	44,921	10,812	0	23,726	58,400	35.14	1.85
IA	23.085	15,042	4,200	0	590	49,400	16.01	3.06
KS	19.871	14,333	292,279	0	718	28,500	12.00	3.20
KY	3.701	15,866	75,750	0	137,197	36,600	22.50	1.31
LA	3.628	50,054	108,107	220,791		24,500	18.52	1.02
ME	.450	5,253	3,696	0		5,390	6.52	.20
MD	1.439	9,170	2,699	0	2,337	30,500	23.66	.23
MA	.188	93,299	10,184	0		25,700	28.02	.21
MI	6.318	44,488	9,314	3,831		139,000	53.10	2.64
MN	17.896	26,906	37,347	No data		216,000	21.40	3.19
MS	4.793	8,509	116,479	168,890		18,200	12.49	1.24
MO	11.765	20,973	319,530	No data	4,623	56,100	26.92	2.79
MT	8.427	1,967	27,102	47,000	14,106	33,900	4.21	1.61
NE	16.309	11,635	88,911	0		16,900	8.50	2.44
NV	.551	1,575	24,643	No data		36,800	3.26	.94
NH	.118	4,363	760	0		6,750	4.82	.26
NJ	.541	49,670	31,325	20,000		44,900	46.80	.44
NM	.976	3,836	26,483	7,136	9,392	42,500	7.36	2.07
NY	4.156	87,001	7,331	0		75,600	63.72	1.54
NC	4.075	38,071	111,209	117,175		57,100	33.82	1.18
ND	19.207	4,946	2,096	1,998		5,110	2.61	1.76
OH	9.680	80,283	6,247	0	45,409	95,900	61.90	1.18
OK	3.990	19,329	514,772	No data	2,356	32,000	18.84	2.65
OR	3.213	12,547	43,658	26,125		45,000	12.74	2.50
PA	3.885	120,113	15,609	0	80,462	90,700	65.26	2.35
RI	.021	7,289	1,311	0		3,210	5.45	.10
SC	2.251	11,885	64,645	388,708		24,300	19.32	.70
SD	14.855	2,358	15,891	No data		12,400	3.70	1.40
TN	3.746	20,579	41,003	No data	7,541	56,000	29.40	1.36
TX	19.014	213,620	42,482	83,255		116,000	73.13	5.56
UT	1.089	11,958	16,707	0	5,858	55,800	6.39	1.06
VT	.575	1,197	366	0		5,280	2.68	.34
VA	2.447	12,946	14,910	30,964	34,326	58,700	32.85	.78
WA	4.946	25,997	35,917	66,777	W(3915)	38,100	21.05	1.53
WV	.511	12,331	82,475	0	102,462	14,600	9.24	8.76
WI	9.340	13,895	8,322	No data		53,900	27.07	.90
WY	1.681	3,509	18,538	0	30,703	17,900	2.87	.59

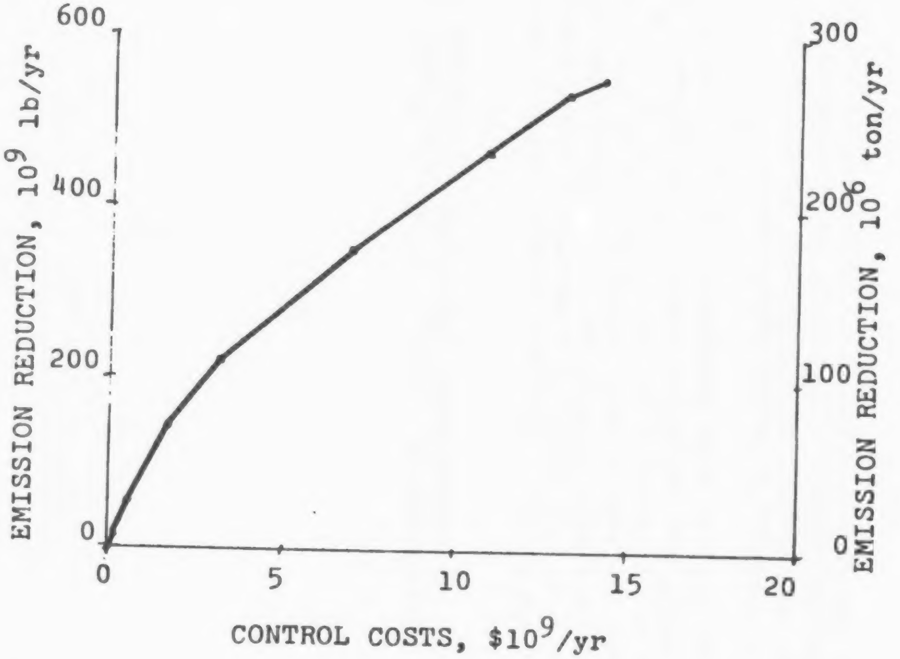
Table 3. OPEN SOURCE EMISSION RATES BY STATE

State	Agriculture		Construction	Forest Fires		Mineral Extraction		Roads	
	Tilling	Wind Erosion		Wild	Prescribed	Coal	Other	Paved	Unpaved
	10^3 tons/yr	10^6 tons/yr	10^5 tons/yr	10^3 tons/yr		10^3 tons/yr		10^6 tons/yr	
AL	5.29	.0168	2.73	102.0	15.64	16.85	39.3	0.149	3.76
AK	.10		.59	646.8	Negl.	.60	127.0	0.011	1.99
AZ	117.	.7909	1.39	28.54	5.19	.19	187.0	0.092	9.74
AR	14.60	.2390	1.41	94.48	4.11	.37	38.0	0.073	9.34
CA	126.	4.4608	48.54	218.8	21.18		171.0	0.803	27.53
CO	158.	.2681	1.17	24.99	.52	.21	33.8	0.089	10.08
CT	.45	.0041	3.33	1.04	0		15.1	0.117	.32
DE	.60	.0136	.10	.05	.04		2.4	0.023	.07
FL	4.99	.1014	7.66	316.6	71.89		235.0	0.386	7.01
GA	8.45	.1165	4.55	41.26	54.35		54.6	0.212	7.01
HI	2.28		.62				9.0	0.026	.08
ID	88.80	.0997	.24	544.0	45.35		17.8	0.030	4.12
IL	151.	2.6682	14.15	11.45	0	49.48	104.0	0.370	7.96
IN	52.4	1.0110	7.73	8.92	0	20.17	58.1	0.229	6.45
IA	142.	.3463	2.53	1.89	0	0.50	49.4	0.104	11.31
KS	239.	.8942	2.45	65.76	0	0.61	28.5	0.078	14.33
KY	15.1	.1258	2.70	62.49	0	116.62	36.6	0.146	4.38
LA	14.4	.1234	8.7	72.97	16.56		24.5	0.121	3.79
ME	1.23	.0094	.87	2.50	0		5.4	0.043	.71
MD	2.09	.0532	1.28	1.42	0	1.99	30.5	0.154	.71
MA	.46	.0038	12.60	8.40	0		25.7	0.182	.68
MI	21.2	.6318	7.43	7.68	.29		139.0	0.345	8.83
MN	99.3	.2863	4.52	30.81	No data		216.0	0.139	11.56
MS	12.9	.0767	1.38	78.62	12.67		18.2	0.081	4.26
MO	61.7	1.2588	3.46	119.8	No data	3.93	56.1	0.175	10.33
MT	200.	.1180	.31	99.6	52.88	0.42	33.9	0.028	7.73
NE	306.	.7991	1.97	20.0	0		16.9	0.056	10.61
NV	68.	1.2265	.22	14.79	No data		36.8	0.021	4.89
NH	.38	.0006	.69	.46	0		6.8	0.032	1.25
NJ	1.63	.0281	8.44	23.49	1.50		44.9	0.304	1.95
NM	50.3	.0517	.61	19.86	1.43	.28	42.5	0.048	10.64
NY	20.1	2.1279	14.62	6.05	0		75.6	0.414	5.16
NC	6.28	.1508	6.40	75.07	8.79		57.1	0.220	3.86
ND	292.	.3841	.80	.47	.10		5.1	0.017	8.80
OH	44.2	.7841	13.65	5.15	0	38.60	95.9	0.403	3.82
OK	38.7	.0918	3.32	115.8	No data	2.00	32.0	0.123	11.86
OR	39.4	.0835	2.12	196.5	21.55		45.0	0.083	12.11
PA	21.6	.0777	20.90	12.88	0	68.39	90.7	0.424	10.10
RI	.08	.0009	.82	.69	0		3.2	0.036	.39
SC	4.28	.0810	1.77	43.64	29.15		24.3	0.126	1.35
SD	210.	.4456	.39	4.77	No data		12.4	0.024	6.37
TN	10.9	.0712	3.33	27.68	No data	6.41	56.0	0.191	4.38
TX	386.	1.2169	37.60	19.12	6.24		116.0	0.476	28.64
UT	78.4	.6730	2.03	10.02	Negl.	.18	55.8	0.042	5.41
VT	1.91	.0328	.17	.22	0		5.3	0.018	1.18
VA	5.29	.0465	2.12	5.39	3.87	29.18	58.7	0.214	2.34
WA	14.6	.0445	4.47	164.3	36.76	.12	38.1	0.137	6.71
WV	2.84	.0051	2.15	74.23	0	87.09	14.6	0.060	3.92
WI	49.0	1.0741	2.18	6.87	No data		53.9	0.176	3.31
WY	56.3	.0807	.59	8.34	0	.62	17.9	0.019	2.44

Table 5. ESTIMATED COSTS OF CONTROL FOR UNPAVED ROAD DUST FOR URBAN AND RURAL ROADS, BY STATES

Estimated Cost of Control \$/lb	Rural Unpaved Roads	Municipal Unpaved Roads	Amount of Unpaved Road Dust Controllable 10^9 lb/yr	Total Cost of Control \$$10^9$/yr
0.000-0.005	DE.	CA, MD, NJ.	13.0	0.047
0.005-0.010	RI.	AK, AZ, DE, HI, NV, PA, CO, FL, IL, IN, KY, MA, NM, OH, OR, RI, TN, TX, UT, VA, WA, WV.	35.8	0.289
0.010-0.015	AZ, CA, NJ.	CT, GA, MO, MT, NE, OK, WI, KS, LA, MN, NY, NC, WY.	72.6	0.904
0.015-0.020	AK, CT, HI, NH, PA.	AL, IA, ME, MS, AK, ID, NH, ND, SD, VT.	23.3	0.409
0.020-0.025	AR, LA, MD, NM, NY, TX, WV.	SC.	89.0	2.00
0.025-0.030	CO, FL, IN, IA, MA, MI, NC, OK, OR, UT, VT, VA.		122.	3.36
0.030-0.035	GA, IL, KS, KY, ME, MN, MO, NE, OH, TN, WA.		122.	3.97
0.035-0.040	AL, MS, MT, NV, WY.		36.5	1.37
0.040-0.045	ID, SD.		17.2	0.731
0.045-0.050	ND, WI.		19.1	0.907
0.050-0.055			0.0	0.0
0.055-0.060			0.0	0.0
0.060-0.065	SC.		2.06	0.129

Figure 1. Unpaved road dust emission reduction versus control cost



APPENDIX B

BIBLIOGRAPHY

This appendix contains the computer output from a bibliographic program called "UNIREF." Written by Dr. Eric Martz of the Harvard Medical School, UNIREF is designed for the maintenance of a file system with a capacity of 10,000 references.

UNIREF has two major functions. The first is to provide a means for cataloging and retrieving reprints. A reference can be classified in UNIREF on the basis of its author, its title, or an assigned keyword. Only one copy of each reference need be kept. The second major capability of UNIREF is to permit file searches and subsequent printing of the reference citations in a variety of bibliographic formats, including those of about a dozen journals. Other formats can be programmed.

On the succeeding pages, the output from UNIREF relating to open sources is presented, as a useful but not exhaustive bibliography.

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APPENDIX C

OPEN SOURCES OF PARTICULATES IN THE MINERAL INDUSTRIES: EXTRACTION AND MILLING

There are several sources of fugitive dust in the mineral industries. The dusts may be fairly innocuous or not, depending upon their chemical and radiological properties. This appendix deals primarily with emissions from tailings piles. Some emphasis will be given here to uranium tailings emissions in particular.

Zoller *et al.*[1] tabulated the activities emitting fugitive dust during mineral extraction and beneficiation:

- overburden removal
- drilling and blasting
- loading
- truck transport
- crushing
- transfer and conveying
- waste disposal
- storage.

From 1930 to 1971, the United States mining industry used 3.65 million acres of land, 0.16 percent of the U.S. land area; of this land 59 percent represented excavation, 20 percent was used for disposal of overburden and other mining wastes, 13 percent for disposal of milling and processing wastes, only 5 percent for the disposal of wastes from underground mining and another 3 percent affected by land subsidence due to underground operations[2]. In 1971 surface mining provided more than 2.7 billion tons of crude ore in the U.S., representing 86 percent of the crude ore production. 1.5 billion tons of wastes were produced by surface mining operations, totaling 94 percent of the total mining industry wastes. (Thus, underground mining contributes a negligibly small amount to open source emissions.) This waste resulted primarily from two operations: overburden removal and ore milling. The overburden, once removed from over the material to be mined and deposited at its storage site, is subject to wind erosion unless stabilization measures (usually, revegetation) are undertaken. Processing metallic ores produces fine wastes, "tailings"; wind erosion from tailings piles is the other large source of fugitive emissions. These two operations are analyzed in this appendix.

Bituminous coal mining accounted for the largest portion of mineral industries land use in the U.S. (from 1930-1971), some 40 percent of the total mining acreage[2]. In 1971 over 50 percent of the coal extracted in the U.S. was obtained by strip or surface mining. Surface mining of coal produces emissions as the overburden is removed. Emission rates for this source are presented and discussed in Appendix A. Other mineral commodities which are mined both underground and at the surface include (with their percentages of total 1930-1971 mining acreage in parentheses): sand and gravel (18), stone (14), clays (5), copper (5), iron ore (3), phosphate rock (2) and uranium (<1).[2] Annual tonnages are given in Appendix A.

The other major source of fugitive emissions in the mineral industries is the wind erosion of non-stabilized tailings piles. The milling of ores results in quantities of solid waste which leave the processing plant as a slurry. The slurry is channeled to a tailings pond where the suspended solids are allowed to settle out. The clarified water can then be reused or discharged. Mining operations which handle 30,000 to 100,000 tons per day of ore are common, and more than 95 percent of the material becomes waste which must be stored in tailings ponds[3].

A tailings pond is essentially a site around which retaining walls are constructed. These embankments are made from tailings or fill. The principal purpose of the pond is to store settled solids indefinitely and to hold water until it becomes clarified by the sedimentation of the solids. The pond must have sufficient area to allow the suspended solids to settle before the water is decanted. After the separation of water and solids, a dried pile of mill tailings remains, a pile sometimes a hundred feet high and covering from less than ten to more than 100 acres. According to Soderberg and Busch[3], a rule of thumb for construction of a tailings pond is to allow 35 acres per 1000 tons of mill production for metal mines (preferably in two separate locations).

To estimate the particulate emission rates due to erosion of tailings piles, the extent of land used for disposal of mill and processing wastes in each state was found[2]. The emission factor for tailings piles reported by Zoller et al.[1] was 14.4 tons per acre per year. This approximate value does not take climatic factors into account. Amick et al.[4] presented an emission factor which did include a climatic factor: 0.133C tons per acre per year; C is the climatic factor described in Appendix A. The 0.133 C value assumes that of the material lost from tailings piles due to wind erosion, 10 percent becomes suspended. In Table C.1 we present the emissions rates for tailings piles based on both estimates. The first column gives the state; the second gives the unreclaimed land area used (1930-71) for minerals other than uranium; the third gives the emission rate estimate based on the Zoller et al.[1] emission factor; the fourth gives the emission rate estimates based on the Amick et al.[4] emission factor (with the climatic factor); the fifth gives the total tailings pile area for uranium (for inactive piles); the sixth and seventh columns are analogous to the third and fourth columns.

To help us decide which factor to accept, we performed a linear regression and a statistical analysis on the two sets of rate estimates. Letting y be the emission rate (10^3 tons/year) from the Amick et al. factor with the climatic correction and x be the emission rate (10^3 tons/year) from the Zoller et al. factor, the linear least squares best fit was:

$$y = 0.21x - 7.8$$

TABLE C.1. PARTICULATE EMISSION RATES IN THE MINING INDUSTRY

STATE	Minerals other than uranium			Uranium Industry (inactive tailings piles only)		
	Land area used for milling, surface waste, not reclaimed, 1930-71(acres)	Emission Rate		Land area used for tailings pile (acres)	Emission Rate	
		10^3tons/yr Zoller et al	10^3tons/yr Amick et al.		(tons/yr) Zoller et al	(tons/yr) Amick et al.
AL	4910	70.7	1.11			
AK	2760	39.7				
AZ	36050	519.	157.	42	.605	.183
AR	3680	52.9	1.02			
CA	44340	638.	142.			
CO	7250	104.	17.0	250	3.60	.585
CT	1190	17.1	.412			
DE	110	1.58	.035			
FL	6510	93.7	2.60			
GA	4810	69.3	1.28			
HI	480	6.91				
ID	15080	217.	30.9	7	.101	.014
IL	8680	125.	5.54			
IN	5100	73.4	2.64			
IA	5290	76.2	4.86			
KS	7490	107.	22.5			
KY	5730	82.5	2.06			
LA	1750	25.2	.442			
ME	830	12.0	.199			
MD	2180	31.4	.754			
MA	1760	25.3	.468			
MI	13690	197.	6.74			
MN	24420	351.	20.5			
MS	960	13.8	.166			
MO	27360	394.	19.3			
MT	4800	69.1	11.6			
NE	1130	16.3	2.79			

TABLE C.1, (cont'd) PARTICULATE EMISSION RATES IN THE MINING INDUSTRY

STATE	Minerals other than uranium			Uranium Industry (inactive tailings piles only)		
	Land area used for milling, surface waste, not reclaimed, 1930-71(acres)	Emission Rate		Land area used for tailings pile (acres)	Emission Rate	
		10^3tons/yr Zoller *et al*.	10^3tons/yr Amick *et al*		(tons/yr) Zoller *et al*	(tons/yr) Amick *et al*
NV	12700	183.	142.			
NH	430	6.19	34.3			
NJ	4450	64.1	1.83			
NM	7450	107.	44.0	222	3.207	1.311
NY	26030	375.	10.0			
NC	5460	78.6	1.96			
ND	610	8.78	1.47			
OH	10720	154.	6.27			
OK	3020	43.5	6.47			
OR	5420	78.0	1.37			
PA	14440	208.	4.03			
RI	190	2.74	.091			
SC	2190	31.5	.612			
SD	2140	30.8	5.29			
TN	10380	149.	1.52			
TX	8390	121.	25.9	190	2.74	.586
UT	23840	343.	118.	180	2.59	.891
VT	3350	48.2	.713			
VA	10200	147.	3.93			
WA	3720	53.6	.742			
WV	6810	98.1	1.18			
WI	4940	71.1	2.89			
WY	2170	31.2	5.92	42	.605	.115

with a correlation coefficient r = 0.73. The rate estimates with the climatic factor included are substantially smaller than the rate estimates without the climatic factor; the mean of y was 18 thousand tons/year and its coefficient of variation (standard deviation divided by the mean) was 2.2. The mean of x was much larger, 120 thousand/year, with a smaller coefficient of variation, 1.2. We chose the rates based on the factor with the climatic correction, the y (Amick *et al.*) values. The inclusion of the climatic factor is sound, and the larger variation was plausible. Note that this may underestimate these emissions, however. The total emissions for the forty-eight contiguous states is 860 thousand tons per year using these estimates (5.8 million tons per year using the higher estimates).

URANIUM TAILINGS

Throughout several states in the West there are abandoned uranium tailings piles, usually larger than 100 acres. These piles can produce the following sources of exposure: eroded particulate material, radon gas and its daughter products, direct gamma radiation. There may also be internal exposure due to the ingestion of surface and ground water contaminated by materials eroded or leached from the piles[5].

To prepare the emission rate estimates for Table C.1, we used the acreages given by Douglas and Hans[5] and both emission factors discussed above. Table C.2 is reproduced from the report by Douglas and Hans[5] to show not only the tailings acreages but also the extents of the contaminate areas in the vicinities of the piles.

An extensive analysis of the control of mineral waste heaps by vegetation was prepared by Donovan et al.[6] Chemical stabilization can also be employed or even a combination of chemical and vegetative stabilization[4]. Uranium tailings present a special problem because the proper stabilization must provide for containment of the radioactive radon gas that emanates from the pile. For example, there is a uranium tailings pile near Salt Lake City, and it is estimated that these 128 acres would need a 22- to 30-foot layer of soil or an 8-foot layer of concrete cement to reduce the emitted radon to "acceptable" levels, unless they are moved; cost estimates for handling this situation have been estimated and have ranged from one-half million to 30 million dollars[7].

TABLE C.2. APPROXIMATE AREAS ENCLOSED BY THE ISO-EXPOSURE RATE LINES AT INACTIVE MILL SITES[5]

Site	Approximate area, (acres)			
	Tailings Pile(s)	Within lines, but excluding tailings		
		40 µR/hr	10 µR/hr	Background
Monument Valley	15	N.C.	(Δ6)[1] 52	N.C.
Tuba City	27	(Δ15)[1] 128	(Δ7)[1] 169	(Δ3)[1] 202
Grand Junction	47	N.C.	N.C.	314
Gunnison	30	12	26	68
Slick Rock (NC)	7	N.C.	12	33
Slick Rock (UC)	19	3	41	81
Rifle (Old)	20	17	44	243
Rifle (New)	21	114	169	312
Durango	10	N.C.	N.C.	N.C.
Maybell	81	322	452	745
Naturita	15	N.C.	N.C.	N.C.
Lowman	7[2]	N.C.	11	16
Ambrosia Lake	104	210	390	617
Shiprock	118	N.C.	(Δ7)[1] 126	(Δ3)[1] 229
Falls City	142	139	256	411
Ray Point	48	19	39	94
Salt Lake City	94	114	198	510
Green River	9	N.C.	(Δ8)[1] 44	(Δ4)[1] 153
Mexican Hat	77	N.C.	(Δ7)[1] 127	(Δ3)[1] 457
Converse County	42[3]	N.C.	88	187

N.C. - Line was not constructed or was not closed (see site summary text for explanation)

(1) - Delta line corresponding to appropriate iso-exposure line (see Appendix B)

(2) - Mill residue stockpile areas

(3) - Includes tailings, overburden piles, and waste dumps (tailings only approximately 2-1/2 acres)

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APPENDIX D

FUGITIVE EMISSIONS OF TOXIC PARTICLES

For the purposes of this report, a toxic particle has been defined as any dust/mist with a threshold limit value (TLV) less than that specified for nuisance particles (10 mg/m^3) by the American Conference of Governmental Industrial Hygienists (ACGIH). We have listed these in Table D.1. Unlike sources of soil-like particulate emissions such as roads, agriculture or construction, open sources of toxic substances are specific to areas where a particular substance is locally manufactured, mined, or disposed of as a waste. Very little work has been done to quantify fugitive toxic emissions. Hazardous substances should not be neglected as contributors to the nonattainment of the primary TSP standard for this country simply because they may not compare in total mass to the suspended soil-like particles.

Four toxic substances are discussed briefly in this appendix. The initial table is a list of substances that may be in particulate form having TLV's less than that designated by the ACGIH for nuisance dusts. It is possible that these substances could contribute to open sources of fugitive particulate emissions during some stage of manufacturing, mining, waste disposal or accidental release into the environment.

LEAD

This report and other papers[1] have determined that the dust from both paved and unpaved roads is a major source of the total suspended particulates affecting the air quality of the U.S. Paved road dust has been reported as having a lead content greater than 1,000 ppm (0.1%).[2] Maxwell and Nelson[3] have calculated a total lead emission factor for fugitive dust from paved roads. They compared their results with emission factors from PEDCo and GCA, as shown in Table D.2. Note that lead emissions due to re-entrained dust are comparable to those from exhaust directly.

ASBESTOS

Major sources of asbestos emissions are the mining of asbestos and the dumping of asbestos manufacturing waste products. Even though a large percentage of the surface rock of the U.S. contains some asbestos, it is only economically feasible to mine this mineral in four states; Vermont and California are the major producers along with Arizona and North Carolina to a lesser extent. Table D.3 shows the asbestos mines and mills operating in the U.S. in 1975.

The United States uses approximately one million tons of asbestos per year. Seventy percent of this annual amount is used for asbestos cement products including pipe, wall siding, roof shingles, wallboard, and insulation

TABLE D.1. PARTICULATE MATERIAL HAVING TLV VALUES (ACGIH^2) LOWER THAN "NUISANCE DUST"

1-10 mg/m^3

Substance[a]	TLV (mg/m^3)
Asphalt (Petroleum) Fume	5
Bismuth Telluride, Se-Doped	5
Borates, Tetra, Sodium Salts	
Anhydrous	1
Decahydrate	5
Pentahydrate	1
Calcium Arsenate	1
Calcium Hydroxide	5
Caprolactum Dust	1
Carbaryl (Sevin)	5
Carbon Black	3.5
Cesium Hydroxide	2
Copper, Fumes, Dust, Mist	1
DDT	1
Dibutyl Phthalate	5
Diethyl Phthalate	5
Ferrovanadium Dust	1
Fluoride	2.5
Fluorine	2
Iron Oxide Fume	5
Iron Salts, Soluble (as Fe)	1
Manganese & Compounds (as Mn)	5
Molybdenum (as Mo)	
Soluble Compounds	5
Insoluble Compounds	10

Substance	TLV (mg/m^3)
Nickel Metal	1
Nitric Acid	5
Oil Mist	5
Oxalic Acid	1
Parafin Wax Fume	2
Phosphoric Acid	1
Phosphorus Pentasulfide	1
Phosphorus Pentachloride	1
Potassium Hydroxide	2
Sodium Hydroxide	2
Sulfuric Acid	1
Tantalum	5
Tin, Inorganic Comp. Except SnH_4 & SnO_2 (as Sn)	2
Triphenyl Phosphate	3
Tungsten & Comp. (as W)	
Soluble	1
Insoluble	5
Welding Fumes (Total Particulate)	5
Wood Dust (Nonallergenic)	5
Yttrium	1
Zinc Chloride Fume	1
Zinc Oxide Fume	5
Zirconium Compounds (as Zr)	5

.1-1 mg/m^3

Substance	TLV (mg/m^3)
Antimony and Compounds	0.5
Arsenic and Compounds	0.5
Baygon (Propoxor)	0.5
Barium (Soluble Compounds)	0.5
Calcium Cyanamide	0.5
Chlordane	0.5
Chromium, Soluble Chromic, Chromous Salts (as Cr)	0.5
Cobalt Metal, Dust, Fume	0.1
Cotton Dust, Raw	0.2
Dieldrin	0.25
Hafnium	0.5
Heptachlor	0.5
Indium and Compounds (as In)	0.1
Lead, Inorganic Fumes and Dust (as Pb)	0.15
Lead Arsenate (as Pb)	0.15
Lindane	0.5

Substance	TLV (mg/m^3)
Nickel, Soluble Comp. (as Ni)	0.1
Particulate Polycyclic Aromatic Hydrocarbons (PPAH) as Benzene Solubles	0.2
Rhodium, Metal Fumes and Dust (as Rh)	0.1
Selenium Compounds (as Se)	0.2
Strichnine	0.15
Tellurium	0.1
Tetraethyl Lead (as Pb)	0.100
Tetramethyl Lead (as Pb)	0.150
Thallium	0.1
Triorthocresyl Phosphate	0.1
Uranium (Natural) Soluble and Insolluble Comp. (as U)	0.2
Vanadium (V_2O_5) as V - Dust	0.5

TABLE D.1.(CONT'D)

$.01$-$.1$ mg/m^3

Substance	TLV(mg/m^3)
Cadmium Dust and Salts	0.05
Cadmium Oxide Fume	0.05
Chromates (as Cr) Certain Insoluble Forms	0.05
Chromic Acid and Chromates (as Cr)	0.05
Lead Chromates (as Cr)	0.05
Lithium Hydride	0.025
Mercury (All Forms Except Alkyl) as Hg	0.05
Silver, Metal and Soluble Compounds (as Ag)	0.01
Vanadium (V_2O_5) as V Fume	0.05

$.001$-$.01$ mg/m^3

Substance	TLV(mg/m^3)
Beryllium	0.002
Platinum (Soluble Salts) as Pt	0.002
Rhodium (Soluble Salts)	0.001

Other Limits

Asbestos: 5 Fibers/cc > 5 μm in Length

Subtilisons (Proteocytic Enzymes as 100% Pure Crystalline Enzyme): 0.00006 mg/m^3

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a. It should be noted that urban suspended dust concentrations are generally $\sim 10^2$ μg/m^3 = 10^{-1} mg/m^3 and would normally contain only a very small fraction of any of the material listed here.

TABLE D.2. COMPARISON OF LEAD RESULTS[3]

	MRI	PEDCo	GCA
I. % Lead in particulate samples			
A. Upwind Hi Vol	0.22-0.46	0.0-2.64[b]	
B. Street loading	0.09-0.22	1.3-2.7(<44μm)	
C. Downwind Hi Vol	0.44-0.98	0.13-3.43	0.6-1.8
II. Lead concentrations (μg/m^3)			
A. Upwind Hi Vol	0.46-0.72	0.00-2.04[b]	
B. Downwind Hi Vol	1.59-2.76	0.39-5.75[b]	1-4
III. Particle size	Fine	Fine[a]	
IV. Lead emission factors (g/veh.mi.)			
A. Total	0.03,0.11,0.06	0.069[b]	
B. Vehicle exhaust	0.02,0.05,0.03	0.036[c]	
C. Road dust reentrainment	0.01,0.06,0.03	0.033[d]	

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a/ Horizontal measurements taken at various distances downwind from the road resulted in increases in % lead.

b/ Based on average of 35 runs.

c/ Average vehicle speed = 40 mph; constant cruise speed.

d/ Calculated by difference, i.e., total emission factor minus vehicle exhaust emission factor.

TABLE D.3. THE UNITED STATES ASBESTOS MINES[4]

Operating Company	Location and Number of Employees				Approximate Weight of Asbestos Produced per Day (metric tons)
	Mine	Employees	Mill	Employees	
GAF	Hyde Park, Vt.	58	Hyde Park, Vt.	143	200*
Coalinga Asbestos Co. Div. of Johns-Manville Corp.	Coalinga, Calif.	20	Coalinga, Calif.	50	Operations Suspended
Atlas Asbestos Corp.	Coalinga, Calif.	20	Coalinga, Calif.	50	100
Union Carbide	Coalinga, Calif.	36	King City, Calif.	50	100
Pacific Asbestos Corp.	Copperopolis, Calif.	36	Copperopolis, Calif.	135	Operations Suspended
Powhatton Mining Co.	Burnsville, N.C.	4	Baltimore, Md.	8	Operations Suspended
Jacquays Mining Corp.	Globe, Ariz.	8	Globe, Ariz.	5	10
Asbestos Mfg. Co.	Globe Ariz.		Globe, Ariz.		Operations Suspended*
Metate Asbestos Co.	Globe, Ariz.		Globe, Ariz.		Operations Suspended*

N.B. 1. All mines open pit except those in Arizona, which are underground.

2. All produce chrysotile asbestos except Burnsville, N.C., which produces anthophyllite.

* Mines having the stated intention to close during 1975.

products. Harwood and Ase[5] have estimated the total quantity of asbestos disposed of as scrap to be approximately 210,000 tons per year. Ten percent of this scrap is fine dust. These scrap products have grown into considerable waste piles with almost no control of the fugitive emissions associated with the waste transfer and dumping (see Tables D.4, D.5). Four major categories of waste dumps are responsible for fugitive asbestos emissions:[6] 1) transfer operations as the materials are dumped, with a relative emission rate of 22 percent; 2) crushing and leveling the waste to form piles, with a relative emission rate of 60 percent; 3) active or new dump areas subject to vehicular traffic, with a relative emission rate of 6 percent; 4) inactive, long term, undisturbed waste piles, with a relative emission rate of 6 percent.

There are also airborne fibers in the vicinity of roadways. In this case, the brake linings of automobiles are the major contributors. Alste et al.[7] report total releases of 17.8 μg/km travelled for passenger vehicles and 54.8 μg/km travelled for light trucks. The fraction of these releases which became airborne was approximately 3.7 percent with the remaining particles being mixed with the road dust or retained by the brake drum. In areas where considerable breaking occurred, an estimate of $5 \times 10^5/m^3$ particles was determined. Each particle consisted of a small bundle of fibers. The majority of the particles had a maximum linear dimension ≤ 2 μm.

PESTICIDES

Manufacturing and Disposal

Unless otherwise noted the figures used here for pesticides come from a recent report by Orcher et al. for EPA.[8] The 1975 production of all synthetic organic pesticides was 7.3×10^5 metric tons. This market was dominated by herbicide production, accounting for more than 48 percent of the total. Herbicide production in 1975 totalled 3.5×10^5 metric tons, a 30.4 percent increase over the previous year. Insecticide production for 1975 reached 3.0×10^5 metric tons or over 41 percent of the total synthetic organic pesticide production for that year. Fungicide production for 1975 was 7.1×10^4 metric tons.

Production of synthetic organic pesticide is expected to increase by an average of 1 percent annually until 1985. At this predicted growth rate, total synthetic organic pesticide production in 1985 will be 8.06×10^5 metric tons.

Inorganic pesticides comprise only about 10 percent of the total U.S. pesticide production. A total of 79 inorganic and metallic-organic pesticides were used in 1973. Of these compounds, 28 were mercury based, 17 arsenic based, 11 copper based, 6 other metal based and the remainder other inorganic compounds.

In 1976, there were 139 pesticide manufacturing plants, distributed throughout 34 states in the U.S. Liquid wastes from pesticide manufacturing

TABLE D.4. TYPICAL WASTE DUMP AMBIENT AIR ASBESTOS LEVELS MEASURED BY ELECTRON MICROSCOPE, OPTICAL MICROSCOPE, AND ATOMIC ABSORPTION

Activity	Distance m	Asbestos Concentration Electron Microscope Fibers/cm^3	Optical Microscope Fibers/cm^3	Atomic Absorption ng/cm^3
No Activity	At Dump	1.2	0.05	0.003
Pipe Crushing	90	22.3	0.25	0.032
Waste Leveling	35	10.9	0.30	0.046

TABLE D.5. FUGITIVE ASBESTOS WASTE EMISSION ESTIMATES BASED ON FIELD MEASUREMENTS

Emission Source	Emission Rate during Active Emission kg/yr	Annual Emission Rate kg/yr
Active Pile	1,100	1,100
Dumping	1,300-6,300	90-430
Inactive Pile	230	230
Crushing & Leveling	500-6,300	6-70
Total		1,400-1,800

often go to a holding pond or evaporation lagoon. Hazardous material evaporates at these sites, resulting in emissions to the atmosphere. Data quantifying pesticide emissions from ponds and lagoons are essentially nonexistent. Archer et al.[8] developed emission factors for both pesticides and ammonia from holding ponds and evaporation lagoons. Their report emphasizes that since pesticides are generally of a high molecular weight and low vapor pressure, it would seem that their evaporation rate would be slow. An important factor that is often overlooked, however, is the remarkedly high activity coefficients of these compounds in water. This can cause high pesticide evaporation rates from ponds and lagoons.

FIELD APPLICATION

Volatilization rates of pesticides from plant or moist soil surfaces can be very large, with losses approaching 90 percent within 3 days for more volatile compounds.[10]

Exact emission factors from field applications of pesticides are extremely difficult to calculate because the quantity of emission depends on the formulation used, the application method, climatic factors and type of crop or area treated. Maybank et al.[9] have related variations in initial off-target drift to meteorological conditions (primarily windspeed) to chemical formulations of pesticide, and to spray parameters. Their results indicate that 30-40 percent of initially deposited butyl ester of 2,4-D evaporates and drifts downwind as vapor in 2 hours following spraying. Drift at the time of spraying with aircraft is approximately 20-35 percent.

Fowler and Bomberger[11] have made summary estimates of 2 aspects of pesticide use:

Source	Emission to Air
Application:	10 percent of total applied
Post-Application:	15 percent of total applied

Although the pesticides are applied as particulates, volatilization makes them sources of vapor rather than of particulates.

TOXIC MINERALS

The emission factors, rates and sources from the mining, storage and disposal of toxic minerals are discussed in the appendix on the mineral industries. Of particular note in terms of hazardous substances are emissions from uranium failings from unstabilized, inactive tailings piles.

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APPENDIX E

FORMULAS FOR ESTIMATING OPEN SOURCE EMISSION RATES

Table E.1 summarizes the formulas used to estimate open source emission rates in this report. More information on the methodology is available in Appendix A. The total open source emission rates were obtained from the sum of the rates listed in Table E.1:

$$E_o = E_A + E_W + E_C + E_F + E_P + E_M + E_S + E_R + E_u + E_T \qquad (E.1)$$

Thornwaite's PE Index was obtained from:

$$PE \doteq 10 \times \sum_{i=1}^{12} [11.5 \times (P_i/(T_i - 10))^{10/9}] \qquad (E.2)$$

where: P_i = total monthly precipitation (inches of rain);
T_i = mean monthly temperature (°F).

In this formula, if T_i was less than 28.4°F, 28.4°F was used. If the term in brackets was greater than 40 for any month, 40 was used.

The climatic factor was calculated from:

$$C = 0.345(\bar{V}_{30})^3/(PE)^2 \qquad (E.3)$$

where: $\bar{V}_{30}$ = mean annual wind speed at 30 feet elevation.

If the speed was measured at a different height (z) then it was corrected to 30 feet elevation by:

$$\bar{V}_{30} = (30/z)^{0.5}\, \bar{V}_z \qquad (E.4)$$

The road use factor was calculated from:

$$U_r = VMT_r/(10 \times M_{Pr} + M_{ur}) \qquad (E.5)$$

where: VMT_r = vehicle miles traveled on rural roads and from:

$$U_u = VMT_u/(10 \times M_{Pu} + M_{uu}) \qquad (E.6)$$

where: VMT_u = vehicle miles traveled on urban roads.

Table E.1. FORMULAS FOR ESTIMATING OPEN SOURCE EMISSION RATES

	where:
agricultural tilling emissions $E_A = (1.1\ s_i/(PE/50)^2)(H)(T_1)/2000$	s_i - implement speed (mph) = 5.5 PE - Thornwaite's PE index H - acreage of harvested cropland T_1 - number of tillings per year = 3
agricultural wind erosion emissions $E_W = (.025\ I\ K\ C\ L'V')(H)$	I - soil erodibility index (tons/acre/yr) K - surface roughness C - climatic factor L' - unsheltered field width factor = 1.0 V' - vegetative cover factor
construction activity emissions $E_C = (1)(D)(E)(M)$	D - duration (months) E - extent (acres/10^6 \$) M - construction expenditure (10^6 \$)
forest fire emissions $E_F = (150\ F_F)(B)/2000$	F_F - available fuel (tons/acre) B - acres burned in wildfires
prescribed burning emissions $E_P = (50\ F_P)(P)/2000$	F_P - available fuel (tons/acre) P - acres burned in prescribed fires
surface coal mining emissions $E_M = ((1.7\ T_{me}) + (0.06\ T_{mw}))/2000$	T_{me} - tons mined in Eastern U.S. T_{mw} - tons mined in Western U.S.
other surface mining emissions $E_S = (2)(T)/2000$	T - tons handled at surface mines
paved road emissions $E_R = (0.013)(M_{Pr} \times 10\,U_r + M_{Pu} \times 10\,U_u)/2000$	M_{Pr} - miles of paved rural roads M_{Pu} - miles of paved urban roads U_r - rural use factor - vehicle miles/mile U_u - urban use factor - vehicle miles/mile
unpaved road emissions $E_u = (0.65\ S_r(\frac{s}{40})(\frac{d}{365}))(M_{ur} \times U_r + M_{uu} \times U_u)/2000$	S_r - road surface silt content (%) s - vehicle speed (mph) d - number of dry days/year M_{ur} - miles of unpaved rural roads M_{uu} - miles of unpaved urban roads U_r - rural use factors - vehicle miles/mile U_u - urban use factors - vehicle miles/mile
tailings pile emissions $E_{\bar{i}} = (0.133\ C)(A)$	C - climatic factor A - acres of tailings piles

The road surface silt content was estimated from:

$$S_r = \frac{3 \times DE \times 15 + NS \times \overline{S}}{3 \times DE + NS}$$

where: DE = miles of dirt or gravel, slag, stone surfaced roads in the state;

NS = miles of primitive, unimproved, and graded or drained roads in the state;

$\overline{S}$ = average soil silt content of land in the state.

APPENDIX F

ESTIMATING THE IMPACT OF IRRIGATION ON AGRICULTURAL EMISSIONS

INTRODUCTION

In some parts of the U.S., especially in the Southwest, irrigation is used extensively. The methodology for estimating soil erosion emissions does take irrigation into account. Our approach to estimating the effects of not irrigating is presented here, along with corrected soil erosion emission rates, which, however, were not used in obtaining the results cited in the main body of this report.

METHOD

The Precipitation-Evaporation (PE) Index was corrected for irrigating by adding the irrigation water to the precipitation for each state. The new PE value was used to obtain an adjusted climatic factor. The fraction of the state's cropland which is irrigated (see Table F.1) was used to weight adjusted and unadjusted climatic factors, forming a weighted climatic factor. This factor was divided by the original, uncorrected climatic factor to form an irrigation correction (Table F.1) which was then multiplied by the uncorrected wind erosion emission rate to form the corrected wind erosion emission rate estimate.

The total cropland wind erosion emission rate estimate changes from about 44 million tons per year to about 36 million tons per year. In only the following states are the corrected estimates 20 percent or more different from the uncorrected: Arizona, California, Colorado, Idaho, Nevada, New Mexico, Oregon, Utah, and Wyoming. Arizona and California have corrected emission rates about 20 and 30 percent, respectively, of their uncorrected emission rates, showing an important contribution to emissions reduction due to irrigation.

Table F.1. CORRECTED WIND EROSION EMISSION RATE ESTIMATES

State	Fraction of Agricultural Cropland Irrigated (1974)	Irrigation Correction (R*)	Uncorrected Wind Erosion Emission Rates (10^3 tons/yr)	Corrected Wind Erosion Emission Rates (10^3 tons/yr)
AL	.004	0.990	47.5	47.0
AK	.048	0.991	0.0	0.0
AZ	.8	0.211	713.	150.
AR	.127	0.928	159.	147.
CA	.746	0.281	3946.	1109.
CO	.257	0.763	882.	673.
CT	.042	0.986	4.1	4.0
DE	.038	0.990	8.6	8.5
FL	.389	0.848	92.2	78.2
GA	.023	0.992	91.5	90.8
HI	.445	0.601	0.0	0.0
ID	.454	0.568	988.	561.
IL	.001	0.999	1721.	1719.
IN	.003	0.999	843.	842.
IA	.002	0.999	2078.	2076.
KS	.075	0.939	4769.	4503.
KY	.002	1.000	122.	122.
LA	.17	0.913	90.7	82.8
ME	.013	0.997	10.4	10.4
MD	.015	0.996	44.6	44.4
MA	.091	0.963	6.4	6.2
MI	.014	0.995	411.	409.
MN	.004	0.998	1611.	1608.
MS	.029	0.987	71.9	71.0
MO	.011	0.994	859.	854.
MT	.094	0.916	1264.	1158.
NE	.196	0.846	5219.	4414.
NV	.917	0.105	1157.	121.
NH	.017	0.997	0.5	0.5
NJ	.153	0.945	15.7	14.8
NM	.447	0.576	842.	485.
NY	.012	0.996	150.	149.
NC	.01	0.997	118.	118.
ND	.002	0.998	3553.	3546.
OH	.002	0.999	823.	822.
OK	.044	0.970	1178.	1142.
OR	.275	0.776	48.2	37.4
PA	.004	0.998	81.6	81.4
RI	.097	0.973	0.9	0.9
SC	.003	1.000	54.0	54.0
SD	.009	0.992	3120.	3095.
TN	.002	1.000	41.2	41.2
TX	.251	0.844	5001.	4221.
UT	.5	0.527	653.	344.
VT	.001	1.000	8.1	8.1
VA	.01	0.997	71.0	70.8
WA	.154	0.888	64.3	54.1
WV	.001	1.000	5.6	5.6
WI	.013	0.994	663.	659.
WY	.5	0.545	639.	348.
TOTALS			44×10^6 tons/yr	36×10^6 tons/yr

APPENDIX G

LINEAR REGRESSION ANALYSIS

Below we describe briefly attempts to predict the measured total suspended particulate (TSP) values from linear combinations of terms involving estimated emission rates. Such modeling is needed to link emission rates with ambient concentrations and thus link the reductions from application of control technology to the improvement of air quality.

Using our own estimates of open source emissions rates, published estimates of point source emissions, and readily available climatological and aerometric data for 1976 we have explored the contributions of open and point sources to measured TSP levels. Three models were considered:

Model 1 - Rollback

$$TSP = a_{10} + a_{11}E_o + a_{12}E_p + a_{13}TSP_a + a_{14}P$$

Model 2 - Modified ADTL

$$TSP = a_{20} + a_{21}\left[\frac{E_o/A}{u}\right] + a_{22}\left[\frac{E_p/A}{u}\right] + a_{23}TSP_a + a_{24}P$$

Model 3 - Simple Box

$$TSP = a_{30} + a_{31}\left[\frac{E_o}{(H \cdot u)\sqrt{A}}\right] + a_{32}\left[\frac{E_p}{(H \cdot u)\sqrt{A}}\right] + a_{33}TSP_a + a_{34}P$$

where: TSP = station-averaged annual geometric mean TSP level ($\mu g/m^3$)
P = precipitation, number of days with rain ($\geq$ .01 inch) or snow ($\geq$ 1 inch) per year
A = state area (1000 miles^2)
E_o = total open source emission rate (10^3 tons/yr)
E_p = total point source emission rate (10^3 tons/yr)
TSP_a = perimeter weighted adjacent states station averaged
u = mean surface wind speed (miles per hour)
$H \cdot u$ = mean annual ((morning + afternoon)/2) mixing height times mean annual wind speed averaged through mixing height (100 m^2/s)
a_{ij} = regression coefficient.

The rollback model was chosen because of its simplicity and its history of application in air pollution policy determination. The others were selected because they are somewhat more physically realistic, accounting at least partially for the effects of wind speed, mixing height, and state area. In the rollback model source contributions to TSP are assumed to be proportional to their emission rates, while in the modified ADTL model, TSP concentrations are assumed to vary proportionally with emissions density and inversely with mean wind speed, and in the box model, source contributions to TSP are proportional to emissions rates and inversely proportional to the volumetric flow rate of dilution air. We modified each of these models slightly, allowing for transport of particles from adjacent states, and for the atmospheric cleansing effect of precipitation. In each of the models the initial empirical constant may be thought of as an allowance for neglected factors which influence TSP, such as secondary particles, rather than as "background," which should be handled adequately by the adjacent states TSP term. The results of ordinary least squares analyses, cf. Table G.1, indicate that even these simple models are descriptively useful. The first column lists the model regression equation under study. The second lists the value of the constant term in the regression and, below it, in parentheses, the value of the t-statistic for the constant; in general, a t-statistic greater than (less than) two means that the factor is (not) statistically significantly different from zero. The third, fourth, fifth and sixth columns contain similar treatments for the factors multiplying the terms in the regressions for open source emission rates, point source emission rates, the TSP levels in adjacent states, and the precipitation. The final column gives both the multiple coefficient of determination (R^2, the fraction of the total variance explained by the model) and, below it in parentheses, the adjusted coefficient, a somewhat better measure of explanatory power of the regression.

Several features of these results should be noted. First, the sign of each empirical coefficient is in agreement with intuition. Second, in each equation point sources contribute more to TSP per ton of emissions than open sources. This would be expected as a result of the differences in particle size distributions, and patterns of source location of these two source classes. Third, the coefficients of adjacent state TSP and precipitation seem to be reasonably stable. Finally, note that the explanatory power (as indicated by the adjusted R^2) of the models increases slightly with increasing physical sophistication of the model.

The relatively low R^2 may be due to improper specification of the model; i.e., specification of a linear relationship rather than a quadratic; failure to account for important variables; errors in the estimation of data; or simply due to the use of highly aggregated data. Often an analysis of the residuals from the regression is a useful tool for uncovering specification errors. Most commonly a plot of standardized residuals versus predicted values is visually inspected. Such an analysis failed to reveal obvious errors. It is also useful to examine in detail the cases yielding the largest residuals. Occasionally such an analysis will reveal errors in data collection, data transcription, and/or inadequacy of models. The three largest positive and three largest negative standardized residuals from each of the three models are presented in G.2. Table G.3 summarizes the model inputs.

No transcription errors were evident in the data for these six states. However, the physical proximity of the three consistently most overpredicted states is suggestive of some systematic deficiency in the data base and/or model.

Table G.1. SIMPLE REGRESSION RESULTS AND SUMMARY OF INPUTS

Model	Factor: constant a_{i0} ($t_{a_{i0}}$)	open sources a_{i1} ($t_{a_{i1}}$)	open sources a_{i2} ($t_{a_{i2}}$)	adjacent TSP a_{i3} ($t_{a_{i3}}$)	precipitation a_{i4} ($t_{a_{i4}}$)	R^2 (R^2_{adj})
Rollback	47.	0.00029	0.011	0.29	-0.094	39
(i=1)	(3.7)	(1.2)	(2.5)	(1.7)	(-1.7)	34
ADTL	49.	0.35	4.4	0.33	-0.15	42
(i=2)	(4.0)	(1.9)	(2.5)	(2.0)	(-3.1)	36
Box	50.	2.2	29.	0.32	-0.15	42
(i=3)	(4.0)	(1.9)	(2.5)	(1.9)	(-3.1)	37

Input	Mean	Standard Deviation
TSP	58.8	12.9
E_o	8150.	7815.
E_p	307.	359.
P	110.6	34.3
TSP_a	55.7	10.0
$E_o/H \cdot u\sqrt{A}$	2.26	1.35
$E_p/H \cdot u\sqrt{A}$	0.120	0.136
A	72.3	87.8
u	9.2	1.40
$H \cdot u$	64.9	10.2

Table G.2. EXAMINATION OF RESIDUALS

model	overprediction		underprediction	
	state	standardized residual	state	standardized residual
rollback	(1) Wyoming	-2.8	Idaho	+3.2
	(2) Montana	-1.9	West Virginia	+1.7
	(3) North Dakota	-1.5	Nebraska	+1.4
ADTL	(1) Wyoming	-2.6	Idaho	+3.4
	(2) Montana	-1.6	Nebraska	+1.6
	(3) North Dakota	-1.5	West Virginia	+1.3
box	(1) Wyoming	-2.6	Idaho	+3.6
	(2) Montana	-1.6	Nebraska	+1.5
	(3) North Dakota	-1.5	W. Virginia	+1.5

APPENDIX H

METRIC CONVERSION FACTORS

LENGTH

1 inch = 0.0254 m
1 foot = 0.3048 m
1 yard = 0.9144 m

AREA

1 ft^2 = 0.0929 m^2
1 yd^2 = 0.8361 m^2
1 acre = 4047 m^2

VOLUME

1 ft^2 = 0.0283 m^3
1 gallon = 0.003785 m^3

TIME

1 minute = 60 s
1 hour = 3600 s
1 day = 86400 s
1 year = 3.154×10^7 s

FORCE/MASS

1 pound (force) corresponds to 0.454 kg (mass)
1 ton (force) corresponds to 909 kg (mass)

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Publication No. EPA-600/7-79-186

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